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WATER EXTRACTIONS OF SOILS AS CRITERIA OF THEIR CROP-PRODUCING POWER

By JOHN S. BURD,
Chemist, California Agricultural Experiment Station

THE PROBLEM

Given sunlight, suitable moisture and physical condition, the limitation on the power of soils to produce crops is variously ascribed to the following general causes:

1. Lack of capacity of the soil to supply the plant roots at all times with watery solutions of the essential elements in proper concentrations.
2. Presence of toxic substances.
3. Lack of physiological balance in dissolved soil constituents.

It is clear that any one or a combination of these conditions may be the cause of low production, even though the remaining conditions may be entirely satisfactory. The instances where the second and third inhibitive causes operate to limit production are perhaps quite numerous. It may even be that, because of frequent occurrence, they are of as much or more practical importance than incapacity of the soil to supply the plant with proper nutrients. Nevertheless we are disposed to regard such instances as special cases and to lay greater stress on the capacity of the soil to deliver up solutes to the growing plant. Studies involving this capacity are obviously more fundamental, in that they have to do with an important function of all soils.

WATER-EXTRACTABLE SUBSTANCES IN SOILS

When we consider this function, we naturally turn to water as the logical agent for the removal and determination of the soluble substances in soils. The application of water as a solvent requires the use of a sufficient amount in proportion to the soil to cause it to come into equilibrium with the true soil solution and thus to insure the complete removal of all dissolved matters when the soil suspension is filtered. Water in excess unquestionably removes not only the substances already in solution but additional quantities somewhat proportional to the amount of water used.[1] Furthermore, we are told that the absorption of solutes by plants is related to the concentration of the soil solution and not to

[1] HOAGLAND, D. R. THE FREEZING-POINT METHOD AS AN INDEX OF VARIATIONS IN THE SOIL SOLUTION DUE TO SEASON AND CROP GROWTH. *In* Jour. Agr. Research, v. 12, no. 6, pp. 369-395, 9 fig. 1918.

the absolute amounts present in the soil. We heartily concur in this opinion; but the impossibility of removing for investigation the true and unmodified soil solution, even from soils whose optimum water content is high, is too well recognized to require discussion. It is true that by the method of Bouyoucos and McCool [1] we can determine the total concentration of the soil solution, but are left in the dark as to the concentration of the individual solutes in that solution.

In the present paper, therefore, our data are presented in terms of the amounts of solutes extracted from soils and not in terms of concentrations. We shall endeavor to use this material in such a way as to justify certain conclusions as to the presence or absence of power on the part of soils to supply the needs of crops and to maintain optimum concentrations in the soil solution. Hoagland,[2] in this laboratory, has shown that, while the total amounts of material extracted from soils by an excess of water are invariably greater than those contained in the soil solution, they are of the same general order of magnitude (as 2 is to 4 or 5), depending on the type of soil. Obviously, then, if the amounts of soil constitutents extracted from cultivated soils can be shown to be relatively high or relatively low, we may legitimately infer that the amounts in the soil solution are correspondingly high or low. We do not mean to imply that figures so obtained would necessarily indicate the existence of an adequate supply of any element, because even low figures might constitute adequacy. The question of adequacy or inadequacy may or may not be answered by such data, but it would certainly reflect the relative magnitudes of the present supply although it might not indicate the soils' power of renewal.

Data presented by Stewart [3] in figures 8 to 20 show that normal seasonal fluctuations in the amounts of the essential elements extracted at different times by water (1 to 5) from a cultivated soil (cropped or uncropped) are likely to be as great as the variations between different soils. He also shows that soils under crop (barley) invariably contain smaller amounts of nitrate, potassium, calcium, and magnesium than their uncropped duplicates, apparently reflecting the inability of soils to maintain their initial concentrations and at the same time supply the needs of growing plants. Since the fluctuations in the amounts of water-soluble substances in soils are known to be quite large and the effect of withdrawal important, it follows that the limitations of soils can best be shown by data obtained during the period in which the withdrawal is actually taking place.

A comparison of the charts referred to above shows that, even though good (uncropped) soils may contain considerably more solutes than poor

[1] BOUYOUCOS, G. J., and MCCOOL, M. M. THE FREEZING POINT METHOD AS A NEW MEANS OF MEASURING THE CONCENTRATION OF THE SOIL SOLUTION DIRECTLY IN THE SOIL. Mich. Agr. Exp. Sta. Tech Bul. 24, p. 592–631, 2 fig. 1916.

[2] HOAGLAND, D. R. Op. cit.

[3] STEWART, G. R. THE EFFECT OF SEASON AND CROP GROWTH IN MODIFYING THE SOIL EXTRACT. *In* Jour. Agr. Research, v. 12, no. 6, pp. 311–368, 24 fig., pl. 1918.

(uncropped) soils, both good and poor soils are reduced to the same general level at the time the crop is growing. The condition of soils under crop is epitomized in Table I.

TABLE I.—*Water extractable matters in soils*[a] *under crop. Average during period*[b] *of low nitrate content*

[Results expressed as parts per million of soil]

	Productivity.												
	Good.							Medium.			Poor.		
Soil No.	1	2	5	6	8	11	14	4	7	10	3	9	12
Nitrate (NO_3)	5	5	4	5	5	4	4	6	5	8	5	5	5
Phosphate (PO_4)	7	5	17	7	12	23	11	9	7	13	6	7	13
Basic ions (K+Ca+Mg)	65	71	108	54	62	72	76	130	69	45	64	54	41

[a] For a detailed description of soils, see STEWART, G. R. Op. cit.
[b] Period covered: Soil 7, twelfth to eighteenth week after planting; soils 12 and 14, eighth to eighteenth week after planting; all others, tenth to eighteenth week after planting.

We observe in Table I a general uniformity in the magnitudes of the various solutes present at the period of depletion in soils of varying productive capacity. Apparently crops first reduce the supply of solutes until these approach a comparatively low and (with a few exceptions) fairly uniform level. Subsequent withdrawals must further reduce the existing supply or be made good by new material coming into solution.

WITHDRAWAL BY CROPS

In the second year's experiments reported by Stewart we installed eight additional containers of soil 1, planted to barley, and harvested and analyzed the crop from time to time. This particular soil was chosen because it was known to be one of our most productive soils and the amounts withdrawn by the crop would presumably represent the usual draft to be expected from the crop under consideration. The data obtained are presented in Tables II and III. In scrutinizing these data it must be remembered that we are not attempting to show the requirements of plants or their nutritive habits, but merely their effect on the soil.

If we now compare these data with the water-soluble content of the soil, we may develop the approximate relation between the demand of barley and the supply in a productive soil. The relation is expressed in the column headed "Ratio." Literally interpreted, the ratio for each ion expresses the number of day's supply contained in the water extract during the several periods covered. Thus, in the case of nitrate we see that there was never less than a nine days' supply in the soil during any period of the growing season. If the plant is capable of absorbing all of

the nitrate present in the water-soluble condition, we have direct evidence that the water-soluble nitrate need only be renewed once in nine days even at this critical period, while at all preceding and subsequent periods the rate of renewal may be much slower. If we apply this same reasoning to all of the ions, we develop the fact that there are always present in this particular soil, in a condition capable of solution in water, at least—

Nine days' supply of nitrate.
Twenty-five days' supply of phosphate.
One hundred and forty-four days' supply of potassium.
Two hundred and sixty-five days' supply of calcium.
Seventy-six days' supply of magnesium.

TABLE II.—*Rate of withdrawal by crop* [a] *as shown by periodic harvesting of soil 1*

[Withdrawals computed to parts per million of soil—50 plants and 1,800 pounds of soil to the unit container]

Date.	Nitrate (NO_3).[b]			Phosphate (PO_4).[b]			Potassium (K).		
	Grams per plant.	Parts per million of soil.		Grams per plant.	Parts per million of soil.		Grams per plant.	Parts per million of soil.	
		Entire.	Per day.		Entire.	Per day.		Entire.	Per day.
May 1 (planted)	0.000	.....	.....	0.000	.....	.....	0.000	.....	.....
June 12	.405	24.85	0.59	.038	2.32	0.055	.133	8.13	0.194
June 26	(?)	.....	.....	.115	7.02	.336	(?)	.....	.....
July 12	.520	31.90	.25	.120	7.35	.024	(?)	.....	.....
July 24	.594	36.40	.32	.132	8.10	.054	.223	13.70	.133
August 7	.629	38.40	.14	.144	8.82	.051	.233	14.30	.043
August 21	.664	40.80	.17	.184	11.20	.170	.276	16.90	.186
August 28	.694	42.50	.24	.194	11.90	.100	.294	18.00	.157

Date.	Calcium (Ca).			Magnesium (Mg).		
	Grams per plant.	Parts per million of soil.		Grams per plant.	Parts per million of soil.	
		Entire.	Per day.		Entire.	Per day.
May 1 (planted)	0.000	.....	.....	0.000	.....	.....
June 12	.012	0.712	0.017	.013	0.816	0.019
June 26	.034	2.092	.098	.031	1.920	.079
July 12	(?)	.....	.....	.036	2.190	.019
July 24	.041	2.530	.016	(?)	.....	.....
August 7	(?)	.....	.....	.044	2.670	.017
August 21	.048	2.940	.014	.049	2.980	.022
August 28	.043	2.650	.....	.051	3.140	.023

[a] Analyses based on varying numbers of plants: June 12, 69 plants; June 26, 42 plants; July 12, 42 plants; July 24, 29 plants; August 7, 28 plants; August 21, 38 plants; August 28, 87 plants.
[b] Nitrate (NO_3) and phosphate (PO_4) computed from the amounts of nitrogen and phosphorus in the crop.

The entire time the crop was in the ground was 119 days. The time to elapse after the period of greatest depletion was 35 days for nitrate, 63 days for phosphate, 77 days for potassium, 63 days for calcium, and 63

days for magnesium. It would appear that there is actually present in the water-soluble condition at the period of greatest depletion more than enough potassium, calcium, and magnesium to supply the entire subsequent withdrawals of the crop at the same rate, and that any renewal or increase of these amounts should be unnecessary if the plant is capable of utilizing the entire supply present.

TABLE III.—*Comparison of water-extractable matters in soil 1 (cropped) with daily draft by plant*

Nitrate (NO_3).				Phosphate (PO_4).				Potassium (K).			
Weeks.	Parts per million of soil.		Ratio.	Weeks.	Parts per million of soil.		Ratio.	Weeks.	Parts per million of soil.		Ratio.
	In soil.	Daily draft.			In soil.	Daily draft.			In soil.	Daily draft.	
1-6, inclusive	69	0.59	117	1-6, inclusive	7	0.055	127	1-6, inclusive	28	0.194	144
7-10, inclusive	4	.25	16	7-8, inclusive	8	.336	24	7-12, inclusive	29	.133	217
11-12, inclusive	3	.32	9	9-10, inclusive	10	.024	417	13-14, inclusive	34	.043	790
13-14, inclusive	8	.14	57	11-12, inclusive	3	.054	55	15-16, inclusive	38	.186	204
14-16, inclusive	3	.17	18	13-14, inclusive	8	.051	157	17th	....	.157	.....
17th	....	.24	.....	15-16, inclusive	5	.170	29	.....	....	.....	.....
.....	....	.....	.....	17th	....	.100	.....	.....	....	.....	.....

Calcium (Ca).				Magnesium (Mg).			
Weeks.	Parts per million of soil.		Ratio.	Weeks.	Parts per million of soil.		Ratio.
	In soil.	Daily draft.			In soil.	Daily draft.	
1-6, inclusive	28	0.017	1,647	1-6, inclusive	15	0.019	789
7-8, inclusive	26	.098	265	7-8, inclusive	6	.079	76
9-12, inclusive	18	.016	1,125	9-10, inclusive	14	.019	736
13-16, inclusive	21	.014	1,500	11-14, inclusive	9	.017	529
17th	.....	.....	.....	15-16, inclusive	20	.022	909
.....	.....	.....	.....	17th	.....	.023	.....

It is evident that nitrate and phosphate are in a class by themselves, in that the supply must be renewed at a much more rapid rate than any of the other ions; but, inasmuch as this soil was highly productive, it must have possessed the power to replenish the soil solution as required. But we have shown heretofore that there is very little difference in the absolute amounts of solutes between good and poor soils under a crop of barley. It follows that figures of the same order of magnitude as those just stated would be obtained by similar computations from the poor soils. We conclude, therefore, that in soils in any degree fit for agricultural purposes (with the possible exception of very abnormal types, such as peat, etc.), the potentially soluble matters are sufficient in amount to meet the requirements of crops; but it does not follow that the plant is capable of drawing upon this supply at the concentrations corresponding to these amounts.

CONCENTRATION AND RATE OF FORMATION OF SOLUTES

Since even our poor soils appear to be able to furnish adequate amounts of all solutes at the most critical periods, we can only ascribe nutritive difficulties of soils to inability on the part of the plant to absorb this potentially soluble supply. The rate of absorption by any plant may be limited by the possible supply and by the concentration of that supply, but we have seen that in all cases which have come under our observation the supply is adequate at all times. We should therefore either measure the concentration of the soil solution itself or evolve some other means of estimating the relative power of soils to maintain an optimum concentration. Our data do not permit us, unfortunately, to estimate the concentration of individual ions in the soil solution, but we may perhaps get an idea of the relative power of soils to maintain or restore a proper concentration by consideration of the data on soils with and without crop. We present in Table IV the seasonal averages of the water-extractable substances in cropped and uncropped soils.

TABLE IV.—*Water-extractable matters in cropped and uncropped soils. Seasonal averages*

[Results expressed as parts per million of soil]

Constituent.	Productivity.							
	Good.							Average all.
Yield in bushels per acre	86.5	84.0	88.4	85.9	87.0	80.1	80.8	84.7
Soil No.	1	2	5	6	8	11	14	
Nitrate:								
Uncropped	131	120	146	141	180	154	96	137
Cropped	36	33	30	43	28	27	23	30
Difference	95	87	116	98	152	127	73	107
Phosphate:								
Uncropped	7	5	18	8	17	30	13	14
Cropped	6	5	17	8	12	26	11	12
Difference	1	0	1	0	5	4	2	2
Potassium:								
Uncropped	40	55	47	33	49	67	75	52
Cropped	31	50	33	27	31	48	59	40
Difference	9	5	14	6	18	19	16	12
Calcium:								
Uncropped	34	37	91	47	66	51	32	51
Cropped	24	19	58	28	34	29	20	30
Difference	10	18	33	19	32	22	12	21
Magnesium:								
Uncropped	23	15	24	21	15	13	6	17
Cropped	13	7	17	10	10	7	4	10
Difference	10	8	7	11	5	6	2	7

TABLE IV.—*Water-extractable matters in cropped and uncropped soils. Seasonal averages*—Continued

Constituent.	Productivity.							
	Medium.			Average all.	Poor.			Average all.
Yield in bushels per acre	70.4	69.4	70.6	70.1	56.2	45.8	50.0	50.7
Soil No.	4	7	10		3	9	12	
Nitrate:								
Uncropped	141	118	130	129	88	54	83	75
Cropped	33	34	39	35	30	18	23	24
Difference	108	84	91	94	58	36	60	51
Phosphate:								
Uncropped	11	7	11	9	7	6	13	9
Cropped	10	7	13	10	6	6	12	8
Difference	1	0	− 2	− 1	1	0	1	1
Potassium:								
Uncropped	45	31	49	42	43	19	30	31
Cropped	40	22	30	31	37	18	20	25
Difference	5	9	19	11	6	1	10	6
Calcium:								
Uncropped	84	61	52	66	32	44	41	39
Cropped	66	41	25	44	25	35	24	28
Difference	18	20	27	22	7	9	17	11
Magnesium:								
Uncropped	26	13	11	16	14	9	9	10
Cropped	22	10	6	12	11	8	6	8
Difference	4	3	5	4	3	1	3	2

EXAMINATION OF UNCROPPED SOILS.—We regard the magnitudes shown as the resultant of the combined effects of previous withdrawals, the time which has elapsed since the soil was last depleted, and the rate at which the soil is capable of replacing solutes removed from the soil solution. A soil might show high figures simply because previous withdrawals by crops had been relatively low or remote in time. Nevertheless it is significant that the average content of the more productive soils for each constituent is relatively considerably higher than the average for the poor soils. We infer from this that high figures ordinarily, but not necessarily, indicate a relatively high rate of elaboration of solutes on the part of the soil. A conspicuous example of an exception to this would be the case of a so-called alkali soil, where large accumulations of solutes might have no relation to the present elaborate power of the soil.

EXAMINATIONS OF CROPPED SOILS.—While all averages of the good soils under crop are higher than the averages of the poor soils, the magnitudes of the differences are quite small. Apparently the crop by withdrawal or indirect effects on the soil tends to reduce the initial amounts of solutes

(and presumably their concentrations) to the same general level in both good and poor soils. It seems probable that, when certain minima are reached, the plant can not absorb solutes, and subsequent withdrawal then depends upon the capacity of the soil to elaborate additional solutes as rapidly as the plant requires them. The figures themselves, however, can not give a direct measure of this capacity, but small variations may possibly reflect important differences in the rate at which solutes are elaborated by different soils.

EQUIVALENCE OF BASES.—If we compare the figures for the individual basic ions in good and poor soils (both in the cropped and uncropped condition), we find numerous instances in which some one or more ions are lower in the good soils than in the poor soils. These discrepancies need not concern us if we regard the figures merely as a means of getting at the power of soils to replenish the soil solution. In fact, this power is more likely to be reflected by the aggregated soluble matters than by individual constituents, and preferably by the aggregate of those constituents of similar chemical properties. We propose, therefore, to consolidate our data for the basic ions in one figure (by addition) for subsequent consideration. If we further consider all of our data with reference to the seasonal requirements of a good crop, we can perhaps indicate why some soils are more productive than others.

In Table II we gave the amounts of the chemical elements found in a good crop of barley produced on soil 1, computed to parts per million of soil. These figures were 42.50 p. p. m. of nitrate, 11.90 p. p. m. of phosphate, 18.00 p. p. m. of potassium, 2.9 p. p. m. of calcium, and 2.98 p. p. m. of magnesium; or in round numbers, 42 p. p. m. of nitrate, 12 p. p. m. of phosphate, and 24 p. p. m. of total bases. We assume these figures to represent the probable requirements of a good crop of barley on all soils and propose to examine our data with reference to the capacity of the various soils to meet this requirement. In Table V we combine all pertinent data available.

NITRATE.—The figures for excess in the good and medium soils show an extraordinary discrepancy between the amounts of nitrate in the uncropped soil and the amounts found in the cropped soil plus the withdrawal of a good crop. We can not satisfactorily account for this discrepancy, which appears to be caused in part by an inhibition of nitrification due to the presence of the crop, but which also represents an actual loss of nitrate from the cropped soil. Since the soils were kept in tight containers, there could be no loss from drainage; and neither denitrification, reduction to ammonia, nor the possible loss of ammonia by way of the plant appeals to us as an adequate explanation. We can only suggest that the presence of a crop may cause such a change in the biological environment of the soil that the nitrogen of nitrates is stored in insoluble (protein) forms in the soil. For our present purposes, however, it is only necessary to point out that such losses appear to be a necessary

incident to the production of a good crop. If the soil is not capable of sustaining such losses, it is extremely probable that crops will suffer from a lack of nitrates.

TABLE V.—*Water-extractable matters with reference to seasonal withdrawals of a good crop*

[Expressed as parts per million of soil]

Constituent.	Productivity.												
	Good.							Medium.			Poor.		
Soil No.	1	2	5	6	8	11	14	4	7	10	3	9	12
Nitrate (NO_3)													
(*a*) In cropped soil	36	33	30	43	28	27	23	33	34	39	30	18	23
(*b*) In a good crop	42	42	42	42	42	42	42	42	42	42	42	42	42
(*c*) Sum (*a*+*b*)	78	75	72	85	70	69	65	75	76	81	72	60	65
(*d*) In uncropped soil	131	120	146	141	180	154	96	141	118	130	88	54	83
Excess (*d*−*c*)	63	55	74	56	110	85	31	66	42	49	16	−6	18
Phosphate (PO_4):													
(*a*) In cropped soil	6	5	17	8	12	26	11	10	7	13	6	6	12
(*b*) In a good crop	12	12	12	12	12	12	12	12	12	12	12	12	12
(*c*) Sum (*a*+*b*)	18	17	29	20	24	38	23	22	19	25	18	18	24
(*d*) In uncropped soil	7	5	18	8	17	30	13	11	7	11	7	6	13
Deficiency (*c*−*d*)	11	12	11	12	7	8	10	11	12	14	11	12	11
Bases (K Ca Mg):													
(*a*) In cropped soil	68	76	108	65	75	84	83	128	73	61	73	61	50
(*b*) In a good crop	24	24	24	24	24	24	24	24	24	24	24	24	24
(*c*) Sum (*a*+*b*)	92	100	132	89	99	108	107	152	97	85	97	85	74
(*d*) In uncropped soil	97	107	162	101	130	131	113	155	105	112	89	72	80
Excess (*d*−*c*)	5	7	30	12	31	23	6	3	8	27	−8	−13	6

When we turn to the poor soils, we see that they all had in the uncropped condition more than enough nitrate to supply the actual amounts withdrawn by a good crop; but all were incapable of sustaining additional losses of the magnitudes, which we must regard as normal.

PHOSPHATE.—The figures for all soils under crop plus the requirements of a good crop are invariably greater than the amounts in the uncropped soils. If the figures for these latter represent in each case the maximum amount of soluble phosphate the soil is able to hold in that condition, it is quite clear that either the plant absorbs insoluble phosphate, or the good soils replace the soluble phosphate as rapidly as it is required by the plant. The latter explanation appears the more probable. But the computed deficiencies of the poor soils are no greater than those of the good soils, nor are the soluble phosphate contents of the former less than many of the latter. The rate of solution of phosphate in the good soils must be very high and we can find no reason to conclude that the poor soils are in any way inferior in this respect.

BASIC IONS.—The amounts of basic ions in cropped soils plus the requirements of a good crop are usually less than the amounts in the uncropped soils. We note two exceptions to this in the poor soils Nos.

3 and 9. For these soils to have supplied the requirements of a good crop and at the same time to have maintained their general level of concentration would have necessitated that more bases come into solution. It is not impossible that they would have responded to the demand for bases, just as they would probably have responded to the demand for phosphate. The important difference between these poor soils and the remaining soils is that the latter would never have been called upon to furnish larger amounts of bases than the uncropped soil shows ability to supply.

CRITERIA OF FERTILITY

The growth of a crop reduces the average nitrate content of soils to a comparatively uniform level in soils of all degrees of productivity (see Tables IV and V). The figures for nitrate in uncropped soils are always higher than the known withdrawals by plants, but may not always be sufficiently high to supply these withdrawals and certain other inherent losses. The relative ability of soils to meet these losses may be inferred from the amounts of nitrate in the uncropped soils.

Except in a few soils containing large amounts of soluble phosphate, the growth of a crop does not reduce this ion to any considerable extent. (The small differences shown approach the magnitude of experimental error.) Furthermore, the figures do not show that good soils possess the power of renewing the soluble phosphate more rapidly than the poor soils. Figures for soluble phosphate can not be considered to reflect the relative power of soils to supply the plant.

The growth of a crop reduces the basic-ion content of soils, but the amounts remaining are still far in excess of the crop requirements. It is not improbable, however, that their concentrations are in some cases falling below the optimum requirements of plants. If this be the case, comparison of the basic solutes of cropped soils may indicate deficiency in this respect. The differences between the basic ion contents of cropped and of uncropped soils are usually, but not always, greater than the demands of crops. These differences therefore express the relative power of soils to supply the crop requirements and to maintain the concentration equivalent to the amounts shown by the cropped soil, without drawing upon greater amounts of solutes than the uncropped soil indicates capacity to supply.

TEST OF CRITERIA.—If we arrange our soils in the order in which they possess the various characters to which attention has been called, we may be able to bring out salient differences between good and poor soils. The order in which the soils occur in each character is frequently determined by very small variations in absolute amount of solutes, but it must be remembered that these are based on considerable numbers of analytical determinations and are probably not vitiated by experimental errors.[1]

[1] STEWART, G. R. Op. cit.

Very small differences at critical points may reflect significant differences in the performance of soils (fig. 1).

All of the poor soils appear among the three lowest in two out of three characters. If we examine the medium soils, we find that Nos. 4 and 10 are among the three lowest in one character. If we draw a line over the three lowest characters as a tentative indicator of the existence of sub-optimal conditions, we find that five of our six medium and poor soils fall below in one or more characters; that the remaining medium soil, No. 7, approaches it in one character; that none of the good soils fall below in any character. It is true that several of the good soils, No. 14, 6, and 1, approach the line very closely, and we do not wish to be understood as attaching too much importance to slight differences in the

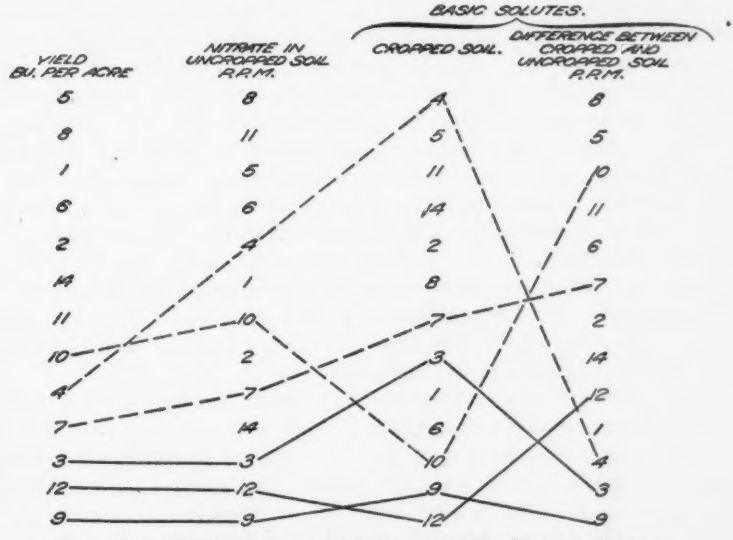
BASIC SOLUTES.
YIELD BU. PER ACRE
NITRATE IN UNCROPPED SOIL P.P.M.
CROPPED SOIL.
DIFFERENCE BETWEEN CROPPED AND UNCROPPED SOIL P.P.M.
5 8 1 6 2 14 11 10 4 7 3 12 9
8 11 5 6 4 1 10 2 7 14 3 12 9
4 5 11 14 2 8 7 3 1 6 10 9 12
8 5 10 11 6 7 2 14 12 1 4 3 9

FIG. 1.—Graphs showing soils arranged with reference to yield and important characters.

magnitudes of these characters. It would appear, however, that the yields of soils 7, 3, 12, and 9 are closely correlated with their nitrate content, but the mediocre yields of soils 4 and 10 can only be accounted for by a reference to other characters.

We conclude that the nitrate content of uncropped soils is the most valuable single criterion for appraising the crop-producing power of soils; that the amount of basic ions in cropped soils is indicative of the extent to which soils tend to maintain their concentrations when subjected to depletion by crops; that the differences in basic-ion content between cropped and uncropped soils may reflect the ability of the soil to meet the demands of the crop without dangerous diminution of concentration and without drawing upon the reserve (insoluble) supply of the soil.

CONCLUSIONS

The evidence presented in the early part of this paper indicates that there is always present in soils, in a condition permitting ready solution in water, enough of the more important chemical elements to supply the immediate needs of crops. It is hardly conceivable that substances in this condition do not represent a potentially available supply. Inasmuch as this supply never entirely disappears, even in the case of nitrates, it would seem that there is no such thing as a lack of available nutrients in soils which are at all productive, but that a plant may still be unable to satisfy its requirements if the concentration with reference to the individual ions falls below certain minima. It is furthermore highly probable that the optimum concentration varies with every soil in accordance with the physicochemical system present in the soil solution. Slight differences in the character of this system may modify in a marked degree the power of a plant to absorb solutes, so that even if we were able to obtain and analyze the true soil solution, we would not necessarily be able to say that any figure for individual ions constituted inadequacy.

Attention has been called to certain characters as reflecting the composition of the soil and its power to produce crops. Inasmuch as these involve three variables to which it is impossible to assign definite relative weights, an exact correlation of productivity with the figures presented is not to be expected. Nevertheless, the correlation between the general magnitudes of the figures presented and the crop-producing powers of the soils studied is sufficiently close to justify the belief that they give expression to the relative power of soils to produce crops, although they are not an exact measure of that power.

We believe that the evidence obtained is sufficient to justify the hope that we may be able to predict, within reasonable limits, the relative crop-producing powers of soils by comparing their figures expressing these characters with similar data derived from soils whose productive power is known. Before such a method is generally applicable, however, it will be necessary to study the behavior of many soils with numerous type crops. This is quite feasible if the various characters can be developed without the enormous number of analytical determinations involved in the present experiments. We believe that this can be accomplished by substituting for our figures, representing the sums of the basic ions, figures obtained for total soluble salts, or preferably direct determinations of the concentration of the soil solution by some such method as that presented in the preceding paper.[1] It is quite certain that we shall never have a precise measure of soil fertility until soils are studied concurrently in the cropped and the uncropped condition and under strict control. The reasons are obvious in that data from the soil under crop can not indicate its latent power, and data

[1] HOAGLAND, D. R. Op. cit.

from the uncropped soil taken alone do not take into account the fact that the solutes in the cropped soils can not be reduced below certain minimum and probably variable limits.

In the present paper we have dealt entirely with chemical criteria because they afford the most convenient expression of the results of the activities of the soil, chemical, physical, and biological. We do not wish to be understood as minimizing the importance of biological studies because we regard living organisms as being the most important single agency, through the formation of nitrates and carbonic acid, in modifying the soil solution. While biological studies have a most important bearing on the proper treatment of soils, the resultant effects of all activities upon these heterogeneous mixtures can only be developed by the actual growth of crops and observation of their effects.

EFFECT OF SEASON AND CROP GROWTH IN MODIFYING THE SOIL EXTRACT

By GUY R. STEWART,[1]
Assistant Chemist, California Agricultural Experiment Station

HISTORICAL REVIEW

The first studies on the water-soluble material of soils were inspired by the results of the investigations of the absorption of plant nutrients carried on by Thompson (55)[2] and by Way (*60*). Their epoch-making discoveries in the year 1850 aroused a widespread discussion of the manner in which the essential compounds might be held in the soil.

Liebig (*39*) was greatly impressed by this work and carried out a series of investigations in which he studied the absorption of calcium phosphate and potassium sulphate. He concluded that, since the phosphate and potassium radicals were so readily absorbed by soils, very little of these essential nutrients could be present in the soil water. The results of lysimeter and drainage studies confirmed him in his belief, and he proposed the theory that the plant roots must be able to draw nourishment directly from the soil particles. At the same time Grouven (*22*) had analyzed the extract from three soils obtained by percolating 6,000 c. c. of distilled water through 2,000 gm. of soil. He attempted to relate these figures to the amount of material that would be brought into solution by the season's rainfall.

Eichhorn (*14*) also studied a soil near Bonn, Germany, in an attempt to obtain a solution which would approximate the moisture existing in the soil. He added 36.5 per cent by weight of water, and allowed it to stay in contact with the soil for 10 days. He concluded that the soil contained all water-soluble nutrients necessary for raising a crop.

This view was severely criticized by Wunder (*63*), who held with Liebig (*39*) that the soil could not furnish sufficient water-soluble material. Schumacher (*52*) replied to Wunder (*63*), upholding Eichhorn's views. Gradually, through the work of Peters (*45*), Jarriges (*31*), Ulbricht (*58*), Hoffman (*28*), Wolff (*62*), and Cossa (*13*), it became evident that the water extract from soils contained the major plant nutrients.

[1] The writer desires to make acknowledgment of the assistance of the Division of Soil Technology, of the California Experiment Station, in selecting the soils employed in the investigation and in performing the physical analyses reported in Table II. The writer is also indebted to Mr. A. W. Christie, of this station, for the performance of ammonification and nitrification studies and to Messrs. H. E. Billings, A. W. Christie, and J. C. Martin, of this Station, for assistance in portions of the analytical work performed in 1916.

[2] Reference is made by number (italic) to "Literature cited," p. 364-368.

The existence of appreciable quantities of water-soluble phosphates was the point longest in doubt, though the results of Heyden (*25*) and Schulze (*51*) established this fact satisfactorily.

The most notable of the early investigations and those which have had the greatest influence on modern work were performed by Schlœsing (*46*, *47*). His method consisted of treating 30 to 35 kgm. of soil with an artificial rain and then collecting the first portions of clear solution which ran through. This he believed to be identical with the actual soil solution, and his was the first attempt to obtain it in an unaltered condition. Schlœsing showed the presence of all the principal elements in this soil extract, and his procedure is still occasionally used in European work. Schlœsing, jr. (*48*, *49*), has continued this portion of his father's work, devoting special attention to water-soluble phosphates, and has concluded that there are differences in the phosphate content of various soils, and also that there is almost enough soluble phosphate present in most soils to supply an average crop.

The first work performed in the United States on the water-soluble material of soils was that undertaken by King (*36–38*), and his coworkers at Wisconsin. This was largely devoted to studies of the nitrate content of cultivated field soils, and was later extended to studies of the total salt content by the use of conductivity methods. The results obtained in this work may be considered to have been merely preliminary to King's more extensive investigations performed in the Bureau of Soils of the United States Department of Agriculture (*34*, *35*).

Before this later work of King's appeared, Whitney and Cameron (*61*) issued a publication from the United States Bureau of Soils which has attracted more attention than any other single paper dealing with water extracts. In it they gave the amounts of phosphoric acid, nitrates, calcium, and potassium found in the water extracts of both good and poor soils under varying conditions. The extracts employed for these analyses were obtained by stirring 100 gm. of soil in 500 c. c. of distilled water for three minutes. After standing for 20 minutes the liquid was decanted into a cylinder of Brigg's (*6*) filtering apparatus and forced through unglazed Pasteur-Chamberland filters under pressure. They concluded that practically all soils gave essentially identical solutions and that even where only a small quantity of one constituent was present, it was sufficient for the growth of a fair crop if the mechanical condition of the soil was good.

It was concluded also that the soil moisture was practically a saturated solution of the mineral substances present in the soil. Consequently, as fast as salts were removed by the plant further quantities were quickly dissolved, thus keeping the solution at nearly the same concentration throughout the growth of the plant. One of the most significant facts claimed to have been shown by the investigation was that the equilib-

rium of the solution quickly readjusted itself, at least as quickly as the plant disturbed it by withdrawing nutrients.

It was therefore believed that the controlling factors in fertility were moisture and the physical condition of the soil, and not fertilizers or plant nutrients.

This was an entirely new viewpoint in soil investigations and has proved extremely stimulating to other workers, though it should be stated that Cameron (*10–12*) has somewhat modified his conclusions in his later writings.

The first portion of the work of King (*34*), which had been carried on concurrently with that of Whitney and Cameron (*61*) in the Bureau of Soils, appeared a year later. It consisted of three papers, which were published privately by the author, while the remaining three were issued from the Bureau of Soils (*35*).

This work constitutes the most extensive investigation so far carried out on the water extracts of soils. The methods employed were the same as those used in the previous investigation of Whitney and Cameron (*61*). The analyses in the preliminary work were performed on the fresh samples of field soil, but later in the investigation, despite the large error involved, oven-dried samples were employed.

The work of the first season was largely of a preliminary nature and was principally carried out at Goldsboro, N. C. Additional samples were taken in Georgia, Virginia, Maryland, New Jersey, Pennsylvania, and Wisconsin. In the second season the work was more intensive and consisted of a study of eight soil types in the four States of North Carolina, Maryland, Pennsylvania, and Wisconsin. The crops used were cotton, peas, beans, corn, and oats.

Applications of fertilizer consisting of 5, 10, and 15 tons of manure and 300 pounds of guano were made to two crops, corn and potatoes. Analyses of the water extracts of the soils from these varied crops were made from three to six times during the season, as well as numerous extracts of the plant saps.

In general, the results and conclusions drawn were diametrically opposed to those of Whitney and Cameron. Relatively large amounts of nutrients were found to be either actually in solution or in such form that they entered into solution when diluted with distilled water. It was also shown that the application of fertilizers materially increased the amounts of salts recovered from the soils. The largest amounts of salts were, as a whole, found where the yields were largest, and the same results were obtained from the examination of the plant sap.

The influence of farm manures was found to increase not only the crop but also the amounts of soluble salts which could be recovered from the soil.

At this same period Gola (*18–21*) published the first of his ecological and chemical studies on the relation of the soil solution to the natural plant environment. He attempted to obtain, by a method founded on that of Schlœsing (*46, 47*), an extract which would be similar to the actual soil solution. The soil was broken up so that it would pass through a 2-mm. sieve and was placed in a glass cylinder, 25 cm. high and 4.5 cm. in diameter. A gentle rain of distilled water at the rate of 25 to 30 mm. per square centimeter per 24 hours, was then allowed to fall upon it. After a period of time, which varied with the soil, drops of solution issued from the lower tubulure, and the process was allowed to continue till 25 to 50 c. c. of "pedolytic" solution had been collected. Gola then subjected the saturated soil to pressure and collected what he called the "pedopiezic" solution.

The total solids, and in some cases the total colloids, were determined in these solutions. From the figures so obtained Gola divided up the possible habitats of various plants into some 32 groups which he believed to be controlled by the solution naturally occurring in the soil. In general, he concluded that the relation between the soil and the organs of absorption of the plant was controlled by the osmotic pressure of the soil solution. High concentrations, and, especially, rapid changes in the solution were likely to be harmful to plants, though many may grow successfully in weaker solutions than were normal for them. The principal factor determining the habitat of plants was the concentration of the solution and, to a lesser extent, its chemical composition.

Snyder (*53, 54*), at Minnesota, carried on a short series of investigations in which he studied the absorption of nutrients from soil extracts which were added to sand cultures, believing this condition comparable to the absorption from the soil water. He arrived at conclusions opposed to those of Whitney and Cameron (*61*) and also criticised their results from theoretical considerations.

Gedroitz (*16*), working in Russia, announced that the concentration of the soil solution fluctuated so rapidly that it was impossible for any water extract to give any indication of the character of a soil.

Mitscherlich (*42*) issued an extremely valuable contribution to the study of the water extract. His method of procedure was essentially different from those previously discussed. He employed for the extraction carbon-dioxid-saturated water at 30° C., the maximum temperature which would probably be encountered in the soil. The proportions of soil and water varied from 1 to 5 up to 1 to 30. At least two dilutions were used in each study, generally 1 to 10 and 1 to 25. The soil and water were placed in a thermostat, with a stirring apparatus running into the center of the flask. Carbon dioxid was passed in constantly and the extraction allowed to continue for 11½ hours.

From the data obtained by these varied extractions Mitscherlich graphically estimated the amounts of additional material which were

dissolved by the water extract over and above that portion which was actually in solution. This was a very valuable differentiation. His conclusion that these graphs could be directly produced and would follow the concentration of the actual soil solution is discussed by Hoagland (*27*) in connection with experimental data bearing on this point.

Mitscherlich was able by his procedure to distinguish between fertilized and unfertilized soils and also between various grades of fertilizer application. An excellent feature of his work was the complete and careful estimation of the factor of error involved for all determinations and its influence on the final result.

Ishcherekov (*29*) published the first of numerous attempts, which are still continuing, to obtain the soil solution by the use of various reagents. Briggs (*6*) and Briggs and McCall (*7*) had previously obtained small amounts of solution from the soil by centrifugal force and capillarity when the soil contained moisture slightly in excess of the optimum. Ishcherekov now attempted to obtain the solution from a soil which was close to saturation by pouring a layer of 0.5 cm. of ethyl or methyl alcohol over the soil and assumed that the first portion of clear solution which ran through was the actual soil solution.

The same author later (*30*) reported a series of studies in which he used the methods of the U. S. Bureau of Soils and from which he drew conclusions which were practically in entire agreement with those of Whitney and Cameron (*61*).

Engels (*15*), on the other hand, reported a series of studies in which he used distilled water, carbon-dioxid-saturated distilled water, and 2 per cent citric acid and concluded that the citric acid was the most satisfactory reagent to estimate the soluble material in soil.

Maschhaupt and Sinnige (*41*) conducted an investigation in which carbon-dioxid-saturated water and 2 per cent citric acid were employed and concluded that carbon-dioxid-saturated water was preferable.

Lyon and Bizzell (*40*) have attempted to estimate the density of the soil solution indirectly by determining the relation of the dry matter formed to the transpiration observed. They conclude that the addition of fertilizer caused an increase in the density of the solution and obtained confirmatory evidence by measuring the density of the soil solution with the Wheatstone bridge.

Van Suchtelen (*17*, *59*) has announced a modification of Ishcherekov's (*29*) procedure in which he uses paraffin oil instead of alcohol. He claims to obtain the soil solution in unaltered form, though the full details of his method have not yet appeared. As the first announcement of this method appeared in 1912, and the last statement of its prospective full publication was made by Morgan (*43*) in 1916, it is to be hoped that it may soon appear in its entirety.

Ballenegger (*2*) has used the methods of the Bureau of Soils, as well as determinations of electrical conductivity, in the study of 75 typical Hungarian soils. He concluded that the character of the water solutions may be used to differentiate the various types of soil. The soils investigated varied from the poor gray forest soils to the very fertile "*alfold*" soils.

Toulaikov (*56*, *57*) believed, like Gola (*19*), that the osmotic pressure of the soil solution was the important factor in plant growth. He found the optimum to be a pressure of three atmospheres and that the growth of wheat was benefited by an increase up to that point.

Pantanelli (*44*) has attempted to study the concentrations of the solutions of soils from Tripoli by determining the electrical conductivity of the liquids obtained by percolation. He was able by this procedure to differentiate between several classes of cultivated and virgin soils.

Hall, Brenchley, and Underwood (*23*) have reported a noteworthy investigation in which the soils from the Rothamstead experiment plots were used. Solutions were prepared using 20 kgm. of soil and 35 kgm. of water, and wheat and barley plants were grown therein. From the analysis of these solutions and the growth of the plants in them it was concluded that—

> The composition of the natural soil solution as regards phosphoric acid and potash is not constant, but varies significantly in accord with the composition of the soil and its past manurial history. Within wide limits the rate of growth of a plant varies with the concentration of the nutritive solution irrespective of the total amount of plant food available. When other conditions such as the supply of nitrogen, water and air are equal, the growth of crops will be determined by the concentration of the soil solution in phosphoric acid and potash; which, in its turn, is determined by the amount of these substances in the soil, their state of combination and the fertilizer applied.

These authors did not find any toxic effect on soils which had grown wheat and barley for even 60 years. Growth in the soil solutions agreed with the growth in culture solutions containing equivalent amounts of phosphoric acid and potash.

In a series of nutritive solutions of various degrees of dilution the growth varied directly, but not proportionately, with the concentration of the solution.

Finally, the authors concluded that the results of the investigation restored the earlier theory of the direct nutrition of plants by means of fertilizers and nullified the theories advanced by Whitney and Cameron (*61*).

Bouyoucos and McCool (*5*) have proposed an ingenious method for determining the concentration of the soil solution directly by means of the freezing point. Use has been made of this procedure in the present investigation by Hoagland, and its application and limitation are discussed in a separate paper (*27*).

Bogue (*3*) has published a brief investigation in which he leached four soils with water and also studied their absorptive capacity for potassium and phosphates. From his work he agreed with Whitney and Cameron that the composition of the soil moisture is not influenced by the chemical composition of the soil, but instead is dependent on the mechanical texture of the individual soil.

Jensen (*32*) reported a series of observations on eight sugar-beet plots at Rocky Ford, Colo. The methods of investigation employed were those of the U. S. Bureau of Soils (*50*). The plots receiving composted manure showed nearly twice as much water-soluble potash in the surface foot as did any of the other plots. The seasonal averages of this element were not appreciably influenced by any other fertilizer treatment. There was a decrease noted in the quantity of water-soluble potash from the middle of May till the middle of July. After that time the quantity increased to approximately the amount that had been found earlier in the season. None of the treatments resulted in a marked increase of soluble phosphates, and the variation in this compound was less than in any other element measured.

Jordan (*33*) has recently published the results of an investigation in which nine soils were analyzed by complete analysis, acid extraction with hydrochloric acid of 1.115 specific gravity, 10 days' leaching with water, *N/200* and *N/25* hydrochloric acid, and five hours' extraction with the last three solutions. Vegetation experiments were conducted with the soils in the greenhouse during two years. At the close of this time it was impossible to establish any relationship between any of the elements determined and the crop-producing capacity. There appeared to be a slight relationship between the total soluble matter in the soil and crop production, but it was not consistent in all cases. The final conclusion was that no method had been developed by which the fertility of a soil could be measured through laboratory investigation.

Harris and Butt (*24*), working in Utah, have studied the effect of varying amounts of irrigation water upon the development of nitrates and soluble salts in cropped and fallow soils. They found notable differences between the cropped soil and the fallow duplicate, but did not find that these differences were related to variation in the crop yield.

SCOPE OF THE INVESTIGATION

The foregoing discussion indicates the contradictory nature of the results already obtained. Two of these moot points especially open to further study are:

1. The relationship between the soluble soil nutrients in cropped and uncropped soils.
2. The relationship between the soil extract and the crop produced thereon.

These questions are the subject of the present study.

METHOD OF ATTACK

It is evident that in any soil a large number of complex factors determine production. These factors, besides influencing the final crop obtained, can also conceivably modify the condition of the plant food in the soil itself. It becomes very clear then that a chemical study of the soil solution can hope to obtain a fair degree of success, only if a number of these modifying factors are subordinated or made comparable.

Prominent among such factors are the influence of physical texture, climate, and moisture. To reduce the effect of physical texture, two types of soils were chosen: silty clay loams and fine sandy loams. The representatives of each class were selected with as uniform a physical texture as possible. Comparisons can therefore be made between the soils within each class, with the assurance that the physical factor is reduced to the minimum.

The effect of climate was made uniform by transporting exceptionally large samples of surface soil to Berkeley. The samples were then sifted and placed in containers which will be described later. Moisture conditions were made as uniform as possible by adding just sufficient distilled water to keep the soils at their optimum content.

SELECTION OF THE SOILS

The soils used in the investigation were chosen according to the mapping of the Bureau of Soils of the United States Department of Agriculture. The silty clay loams were all chosen from the Yolo series. Of these, three were taken from the Sacramento Valley and three from the Santa Clara Valley. The past history of all these soils was very different, as shown in Table I. The crops grown on them were equally divided between orchard crops (prune, almond, peach) and field crops. None of the orchards had received any special treatment. Among the field soils, the sample from the University Farm at Davis was the only one which had been manured, though its cropping was no more varied than No. 4 from the Santa Clara Valley. Soil 3 from Yolo had a less varied history than any other in either set. This soil had been under cultivation since about 1860, and, except for two years in sugar beets, 1911 and 1912, it had been steadily cropped with wheat or barley each year. Its past production was stated to be good, fully the average for that section, though no exact record had been kept of the yields.

TABLE I.—*Classification and history of the soils used in this investigation*

Soil No.	Soil series and type.	Origin.	Crop grown.	Past treatment.
1	Yolo silty clay loam.	Sacramento Valley (University Farm, Davis).	Field crops...	Early planting of grain; 1909-1911, barley; 1912, fallow and manure; 1913-14, barley.
2	.....do.....	Sacramento Valley (Yolo).	Almond orchard.	Formerly grain; almond orchard 12 years old.
3	.....do.....	.....do.....	Barley.....	Planted about 1860; since then barley and wheat, except sugar beets in 1911-12.
4	.....do.....	Santa Clara Valley (San Jose).	Field crops..	Originally grain; later orchard; several years alfalfa; three years field crops.
5	.....do.....	.....do.....	Prunes.....	Originally grain; prune orchard about 20 years old.
6	Yolo clay loam...	Santa Clara Valley (Lawrence).	Peaches.....	Originally grain; peaches for 8 years; heavy crop, about 12 tons per acre.
7	Hanford fine sandy loam.	Southern California (Arlington).	Oats.....	Originally grain; about 1890 put into alfalfa for 13 years; potatoes 2 years, alfalfa 4 years, oats 5 years; yield of oats, 4 tons of hay per acre.
8	Fresno fine sandy loam.	San Joaquin Valley (Fresno).	Seedless grapes.	Originally grain; 14 years in Sultanina (Thompson Seedless) grapes. Production about 2 tons of raisins per acre for last 6 years.
9	Kimball fine sandy loam.	Southern California (Redlands).	Navel oranges.	25 years in oranges; previously bare land. A great variety of fertilizers had been used.
10	Tejunga fine sandy loam.	Southern California (San Fernando Valley).	Peaches.....	Originally 15 years in prunes; now 10 years in peaches; small amount or manure the only treatment.
11	Madera fine sandy loam.	San Joaquin Valley (Kearney Park).	Navel oranges.	Orange trees about 15 years old.
12	Arnold fine sandy loam.	San Joaquin Valley (foothills).	Oats.....	In cultivation about 40 years; early crops largely wheat; last four or five years biennial crops of oats; alternate year summer fallow.
13	Unnamed fine sandy loam.	Mendocino County coast.	Virgin.....	Very shallow soil, about 1 foot in depth underlain by clay subsoil.
14	Standish fine sandy loam.	Honey Lake region.	.....do.....	Desert soil, small shrubs and weeds, natural growth.

The fine sandy loams had an even more varied past history. Three of these soils were from southern California. One of these was from a Redlands orange grove which had been treated in the past with a great variety of fertilizers. A second was from a peach orchard of the San Fernando Valley, and the third from the Riverside area had been devoted to field crops.

Three fine sandy loams were obtained in the San Joaquin Valley. Two from the vicinity of Kearney Park, in oranges and Sultanina (Thompson Seedless) grapes, had an excellent record for past production. The third from the foothills near Oakdale was purposely chosen from a body of Arnold fine sandy loam where the growth of oats was unusually small, though the soil was normal in depth and drainage. The last two fine sandy loams were virgin soils. One of these (No. 13) came from the coast of Mendocino County, and was an extremely poor, shallow soil. In fact, it later developed that this soil was very acid; therefore no deductions have been drawn from the results obtained with it. The other virgin sample was obtained from the Honey Lake area. This soil was considered to be rather in the class of desert soil, but was not especially deficient in organic matter.

The soils of both types were selected to include as many past treatments and crops as possible. They had, of course, been exposed to very different climatic influences. This is an unavoidable factor in California, with its great diversity of local conditions. It is believed that these various influences have been largely neutralized by the cropping of the first season, 1915, under uniform conditions. Greater emphasis is therefore attached to the results of the past year (1916).

The attempt was also made to choose soils which, though of uniform physical texture, would have a very different crop-producing power. In this way it was hoped that some light might be thrown on the relation between yield and water-soluble nutrients.

In Table II are given the moisture equivalents, hygroscopic coefficients, specific heat, and mechanical analyses of the 14 soils. Moisture equivalents are obtained by the method of Briggs and Shantz (*8*); hygroscopic coefficients by the method of Hilgard (*26*). Specific heat was determined by heating 20 gm. of soil in a tin-foil container until it reached a temperature of approximately 100° C. It was then lowered into an insulated tank of water of known temperature and volume. The amount of heat contained in the soil was measured by the increase of temperature of the water. The mechanical analyses were performed by the method of the Bureau of Soils (*9*). It should be noted that the analyses as reported were performed on the same samples which were used for the chemical analyses. These samples had been passed through a 1-mm. sieve. This was done in order that the chemical and physical analyses should be made on identical portions. The percentage of gravel by this screening process is also stated, so that the mechanical analyses

may, if desired, be recalculated to the usual form. A study of these figures shows that the members of each group of soils in physical texture are as similar as was desired. From these analyses Mr. C. F. Shaw, of this Station, states that the silty clay loams would be accurately classed as—

clay loams with a very high percentage of fine sand and silt, and that with the exception of No. 6 they would function as very uniform silty clay loams. No. 6 would be classed as a clay.

The fine sandy loams are considered to be quite uniform in texture, so far as porosity, ease of root penetration, and behavior under cultivation are concerned. The moisture equivalents are very different, so that at first glance it would appear that the plants would be unequally supplied, especially in the fine sandy loams. It will be pointed out later, however, that this view does not consider the fixed or "unfree" water of the soil. The amount of moisture, therefore, which is available to the plants, as shown by the wilting coefficient, and also the amount which affects the concentration of the soil solution, can not be judged from the moisture equivalent alone.

TABLE II.—*Moisture equivalents, hygroscopic coefficients, specific heat, and mechanical analysis of experimental soils*

MOISTURE EQUIVALENTS

Test No.														
Soil.....	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Test 1.....	27.51	25.23	27.44	23.62	24.12	30.57	13.61	7.77	9.95	18.41	16.29	9.15	18.57	17.84
Test 2.....	27.27	25.06	27.10	23.95	23.29	30.09	13.45	7.94	9.27	17.98	16.00	10.00	19.02	17.45
Test 3.....	27.08	24.93	27.26	24.53	24.38	30.24	13.06	8.24	9.73	18.76	16.61	9.72	18.22	17.99
Test 4.....	27.21	24.77	27.69	24.01	23.75	30.22	13.10	8.30	10.53	.....	16.24	10.01	18.43	.....
Average...	27.28	25.00	27.37	24.03	23.88	30.28	13.31	8.06	9.87	18.38	16.28	9.72	18.56	17.99

HYGROSCOPIC COEFFICIENTS

Test 1.....	7.95	6.09	8.33	5.49	8.11	8.82	2.83	1.15	1.57	2.93	3.14	1.85	1.31	4.72
Test 2.....	7.92	6.36	8.08	5.77	8.14	8.84	2.94	1.20	1.49	2.95	3.18	1.68	1.30	4.76
Average...	7.94	6.23	8.20	5.63	8.12	8.83	2.89	1.17	1.53	2.94	3.16	1.77	1.31	4.74

SPECIFIC HEAT

Test 1.....	0.2122	0.2057	0.193	0.1901	0.2246	0.243	0.1969	0.1758	0.230	0.184	0.2480	0.1807	0.1933	0.224
Test 2.....	.2095	.2042	.200	.2008	.2245	.242	.1876	.1661	.234	.188	.2501	.1656	.1860	.230
Average...	.211	.205	.1965	.1954	.2245	.2425	.1918	.1709	.232	.186	.2490	.1731	.1897	.227

TABLE II.—*Moisture equivalents, hygroscopic coefficients, specific heat, and mechanical analysis of experimental soils*—Continued

MECHANICAL ANALYSES

[Averages of two analyses]

Kind of soil.														
Soil.....	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Fine gravel (1–2 mm.).	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.016	0.00	0.00	0.00	0.04	0.00
Coarse sand (1–1.5 mm.)	.15	.60	.60	2.09	1.84	.746	2.82	1.95	9.986	1.57	2.77	4.99	7.77	3.09
Medium sand (0.5–0.25 mm.).	.23	1.50	1.04	1.24	1.70	.574	2.87	3.19	6.308	2.94	2.818	4.38	14.55	4.05
Fine sand (0.25–0.010 mm.).....	1.69	8.00	3.53	5.47	9.61	1.786	15.60	21.22	21.730	16.62	20.945	23.27	13.49	24.54
Very fine sand (0.01–0.05 mm.).	32.62	31.26	26.28	30.32	32.73	21.775	53.67	50.63	43.67	38.76	39.34	46.24	15.70	38.94
Silt (0.05–0.005 mm.)	42.68	36.97	38.12	37.99	30.52	37.415	16.01	17.57	10.87	26.25	19.075	9.61	34.72	15.55
Clay (0.005–0 mm.).....	24.17	22.47	28.47	25.08	24.72	39.380	9.77	5.56	8.19	13.37	14.62	9.44	12.95	13.87
Sum of percentages.....	101.54	100.80	98.68	102.19	101.12	101.676	100.58	100.12	100.77	99.51	99.568	97.93	99.22	100.04
Gravel removed by previous screening..	.11	.09	.39	6.15	3.38	.11	3.64	.99	6.41	.59	2.12	1.57	1.15	2.21

In choosing the soils in the field the following plan was adopted. One soil of each type was taken as the typical sample. Then each succeeding member of that group was chosen by comparison with a small sample of this type. This same small sample was carried while all the work was being done on that group, and constant comparisons were made when there was ground for doubt. In this way it was believed that each member of a group would approach very closely to the other members in general physical texture.

The samples in each case were taken from the top foot of soil. Preliminary borings with a soil auger were made in order to ascertain whether the subsoil was free from hardpan or other abnormal factors which might influence the surface soil. The amount of each of these samples was 2½ tons. The soil was shipped in new, heavy burlap sacks holding approximately 100 pounds each. Every attempt was made to prevent undue drying or exposure to sunshine after the soil was sacked.

Upon the arrival of the samples in Berkeley they were immediately passed through ¼-inch concrete sieves to obtain a uniform physical texture. This work was performed with all possible expedition, and it is believed that they had a normal bacterial flora when placed in the containers. None of the soils, except No. 14, was actually air-dry when finally prepared for use. The ammonifying and nitrifying powers of the soils have been determined as a test of normal biological activity. This work was performed at the beginning and close of the season of 1915 and at the end of the growing season in 1916. The tests were carried out

by the well-known tumbler method. All the soils showed a satisfactory capacity for ammonification.

At the close of the season of 1915, soils 12 and 14 were noticeably lower in nitrifying power than the others of the group. At the close of 1916, soil 12 alone showed a significant lower range in nitrification. With these exceptions the soils gave results which indicated normally active bacterial floras. The detailed data are not considered sufficiently illuminating to justify their inclusion in this paper.

SOIL CONTAINERS AND INSTALLATION

The soil containers selected were 30 inches wide, 60 inches long, and 18 inches deep. They were made of No. 24 galvanized iron and were thoroughly coated with asphaltum varnish. When filled, each contained approximately 1,700 pounds of soil. The design of the containers

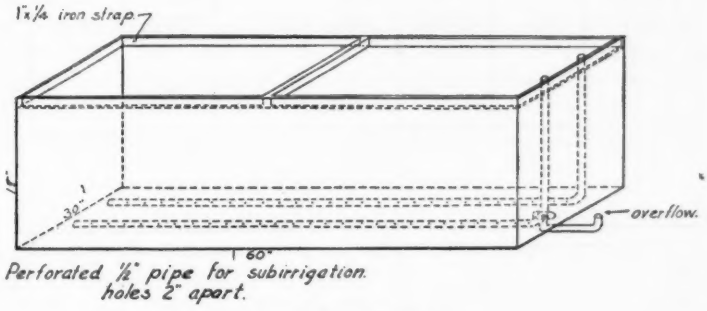

FIG. 1.—Design of soil containers.

is shown in figure 1. It will be observed than an outlet is placed in the bottom at one end. This outlet not only prevented the accumulation of excess water, but also gave additional aeration to the lower soil. The escape pipes may possibly be seen in the illustration of the wire house inclosing the containers (Pl. 14, A).

Distilled water was the only moisture used at any time. This was added partly between the rows of grain by a long-spouted sprinkling can and partly by subirrigation through the two perforated pipes running from end to end of the containers. So far as possible, only enough water was added at one application to keep the soil at optimum moisture. It was found possible to observe the moisture condition quite closely by drawing out a core of soil with an 18-by-¾-inch cheese trier, and then replacing the soil.

The containers numbered 28, 2 for each soil, and were arranged on level mud sills in two duplicate sets, as indicated in the accompanying diagram (fig. 2). By the above arrangement the smallest possible

external surface of each container was exposed to any temperature change. These changes were further minimized by surrounding the set of containers with a boxing, 18 inches high, placed 6 inches from the outside of the entire group. This 6-inch space was then filled compactly with local soil. The insulation furnished by this arrangement was excel-

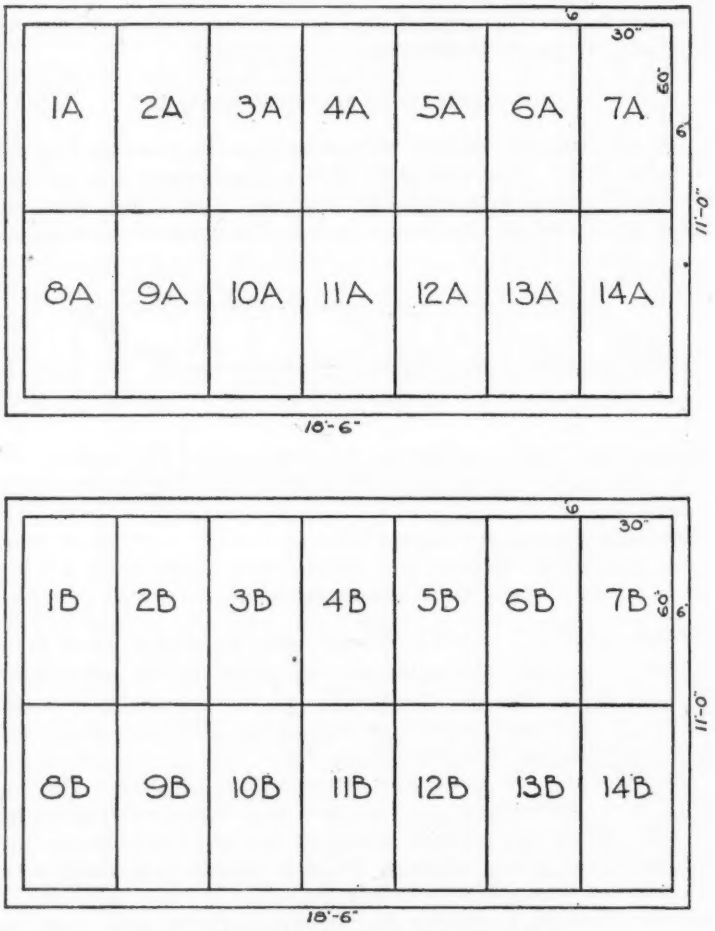

FIG. 2.—Diagram of the arrangement of the soil containers.

lent. No difference in growth was observed in any portion of the containers.

Protection from birds was assured by a framework, 4½ feet in height above the containers, covered with 1-inch-mesh wire netting. The general arrangement of the two sets is shown in Plate 14, A.

During the growing season selected for these experiments, from May to September (the first season, however, being from June to October), very little rain falls in Berkeley. To protect the soils from flooding by any heavy showers that might occur, waterproof canvas covers have been provided and have been put over the wire houses in a few emergencies. During the season of heaviest rains these covers are kept on, and the containers are never flooded or subjected to leaching by rain. In this season between crops the soils are watered with distilled water at intervals, so that they are close to the optimum at all times. It is, of course, true that this is not comparable to the seasonal changes to which field soils are subjected. On the other hand, such seasonal changes of rainfall and drouth are never comparable for any two seasons or any two places. Many orchard soils in this State, by constant cultivation and irrigation in the summer, retain a very regular moisture supply in the soil. The moisture conditions of this experiment are, in fact, very similar to those found in such cases. The orchard, in addition, is subjected to occasional large excesses of water from rainfall.

After filling the containers with the prepared soils, the excess portions of sifted soil were stored in the set of tightly covered bins shown in Plate 14, B. This soil was available for supplying the small portions removed by sampling and also furnished a stock for additional studies.

ANALYTICAL PROCEDURE

In the season of 1915 the analytical methods used were those outlined in United States Department of Agriculture Bureau of Soils Bulletin 31 (*50*). With pure solutions containing only a single compound the determinations obtained by these methods are very satisfactory. Before the close of the season considerable doubt was felt in regard to certain of the results obtained. This applied especially to calcium, potash, and phosphate. Before entering upon the work of the season of 1916 a series of studies were outlined to test the accuracy of the methods which had been in use. The preliminary work previously performed by the procedures in Bulletin 31 had all been carried out with solutions which contained only one pure salt of the radical to be determined. Under these conditions the results were extremely accurate.

In the studies now undertaken three sets of solutions were prepared to simulate as closely as possible the highest, average, and lowest concentrations ordinarily obtained in soil extracts. The salts used were monocalcium phosphate, calcium nitrate, magnesium sulphate, potassium chlorid, and ammonium chlorid. The solutions were made up with distilled water which had stood in ordinary glass bottles and so contained small amounts of sodium and silica, though not of course comparable to the amounts which occur in water extracts from soils.

Quadruplicate portions of these solutions were analyzed without further treatment. Large aliquots from the same stock bottles were also passed through new and old Pasteur-Chamberland filters, and some portions were treated with G. Elf carbon black. These treatments were included to check the possible effect of absorption of elements by the filter candles, as well as the effect of the carbon black which was used to decolorize soil extracts containing organic matter.

Table III gives the results of the analyses of the untreated and of the filtered solutions. It will be seen that the determinations of ammonia and nitrate are satisfactory throughout. The methods used are essentially those almost universally applied in sanitary water analysis (*1*) and with the proper precautions are not believed to be open to criticism. The results for potassium, calcium, sulphate, and phosphate are seen to be extremely inaccurate in the lowest concentration. Of these the calcium is by far the most questionable. The error in the determination of this element is so large that the results for calcium obtained in 1915 have consequently been discarded. Even with the potash and phosphate the percentage of error is very large in some determinations. In the higher range of concentrations the results are much closer throughout, and if it were possible to confine all the work done to such solutions there would perhaps be no objection to the methods employed. In many solutions smaller concentrations of one or two elements are frequently encountered. In such a case the error may be 50 per cent or more, either plus or minus. Such a variation can readily obscure any significant change in concentration. It became necessary to obtain a more reliable procedure for potassium, calcium, and phosphate, all of which are extremely important elements in any study of soluble plant nutrients.

TABLE III.—*Analysis (in parts per million) of dilute, average, and strong solutions by the methods outlined in United States Department of Agriculture Bureau of Soils Bulletin 31*

Solution and treatment.	NH_3		NO_3.		K.		Ca (turbidimetric).		Mg (colorimetric).		SO_4 (turbidimetric).		PO_4 (colorimetric).	
	Theory.	Determined.	Theory.	Determined.	Theory.	Determined.	Theory.	Determined.	Theory.	Determined.	Theory.	Determined.	Theory.	Determined.
Dilute, untreated	0.50	0.48	4.00	4.08	1.2	5.72	1.5	1.76	0.50	0.51	1.99	2.72	1.0	2.5
	.50	.48	4.00	4.08	1.2	1.92	1.5	1.68	.50	.46	1.99	2.68	1.0	2.4
	.50	.48	4.00	4.00	1.2	1.92	1.5	3.80	.50	.49	1.99	3.60	1.0	1.6
	.50	.48	4.00	4.16	1.2	1.80	1.5	2.08	.50	.44	1.99	2.60	1.0	1.9
Dilute, filtered through Pasteur filters	.50	.45	4.00	4.16	1.2	3.40	1.5	.48	.50	.44	1.99	2.68	1.0	1.6
	.50	.45	4.00	4.08	1.2	3.60	1.5	1.84	.50	.44	1.99	2.60	1.0	1.7
	.50	.40	4.00	4.08	1.2	3.20	1.5	1.24	.50	.46	1.99	2.76	1.0	1.9
	.50	.45	4.00	4.08	1.2	3.12	1.5	1.60	.50	.44	1.99	2.72	1.0	1.7
Dilute, treated with carbon black and filtered through Pasteur filters	.50	.45	4.00	3.92	1.2	2.12	1.5	1.44	.50	.56	1.99	2.88	1.0	1.7
	.50	.40	4.00	3.92	1.2	2.72	1.5	1.28	.50	.56	1.99	2.80	1.0	1.6
Dilute, passed through new Pasteur candles	.50	.42	4.00	3.68	1.2	3.24	1.5	1.92	.50	.54	1.99	2.60	1.0	1.5
	.50	.40	4.00	3.84	1.2	2.64	1.5	1.08	.50	.49	1.99	3.68	1.0	1.7
Average, untreated solution	1.50	1.66	20.00	19.2	6.00	4.30	7.5	8.00	2.50	2.36	9.8	9.00	5.0	6.0
	1.50	1.58	20.00	19.6	6.00	5.10	7.5	7.70	2.50	2.41	9.8	8.8	5.0	5.2
	1.50	1.58	20.00	20.0	6.00	5.88	7.5	7.50	2.50	2.30	9.8	10.0	5.0	5.2
	1.50	1.58	20.00	20.0	6.00	6.24	7.5	7.90	2.50	2.36	9.8	8.8	5.0	5.0
Average solution filtered through Pasteur filters	1.50	1.61	20.00	19.2	6.00	6.64	7.5	7.90	2.50	2.66	9.8	9.6	5.0	4.8
	1.50	1.61	20.00	18.8	6.00	8.69	7.5	8.00	2.50	2.61	9.8	9.2	5.0	4.0
	1.50	1.61	20.00	19.2	6.00	8.40	7.5	7.60	2.50	2.61	9.8	8.8	5.0	4.6
	1.50	1.64	20.00	18.8	6.00	8.00	7.5	7.70	2.50	2.66	9.8	9.2	5.0	5.0
Average solution treated with carbon black and filtered through Pasteur filters	1.50	1.64	20.00	18.6	6.00	6.00	7.5	8.00	2.50	2.61	9.8	13.4	5.0	4.3
	1.50	1.64	20.00	18.6	6.00	6.00	7.5	8.20	2.50	2.43	9.8	11.8	5.0	4.6
Average solution passed through new Pasteur filters	1.50	1.64	20.00	19.2	6.00	6.96	7.5	8.30	2.50	2.30	9.8	11.8	5.0	4.8
	1.50	1.64	20.00	18.0	6.00	6.56	7.5	7.80	2.50	2.41	9.8	11.8	5.0	4.7
Strong solution, untreated	3.00	3.07	38.00	37.6	12.00	10.66	15.0	16.60	5.00	5.31	19.7	20.0	10.0	10.4
	3.00	2.94	38.00	37.6	12.00	10.66	15.0	16.40	5.00	4.80	19.7	19.0	10.0	10.8
	3.00	2.94	38.00	38.4	12.00	13.12	15.0	16.40	5.00	4.74	19.7	18.2	10.0	10.4
	3.00	2.94	38.00	38.4	12.00	11.76	15.0	17.00	5.00	4.93	19.7	19.0	10.0	10.2
Strong solution passed through Pasteur candles	3.00	2.86	38.00	38.4	12.00	12.32	15.0	16.60	5.00	4.93	19.7	19.5	10.0	9.8
	3.00	3.07	38.00	37.6	12.00	12.49	15.0	16.80	5.00	4.80	19.7	18.2	10.0	9.2
	3.00	2.90	38.00	37.6	12.00	13.56	15.0	16.40	5.00	4.86	19.7	18.5	10.0	9.2
	3.00	2.94	38.00	38.4	12.00	11.60	15.0	16.00	5.00	4.74	19.7	18.7	10.0	9.4

The determination of magnesium, though it is the same procedure as used for phosphate, has, at least in this series, given more accurate results. The same standard solution is used in this method as in the phosphate determination, and has a value approximately one-fourth as great when expressed in terms of magnesium, a fact which would decidedly tend to reduce the percentage of error in the final result. The same colorimetric procedure for magnesium is still in use, as no more satisfactory method for small amounts of this element has so far been developed. The sulphate determination is seen to be more accurate than that of calcium, but the error in low concentrations is from 35 to 85 per cent. This procedure has therefore been dropped and the sulphate determinations are not included in the 1915 charts.

In planning the work for 1916 it was evident that a smaller number of more accurate determinations were to be preferred to a larger number on which little reliance could be placed. With this idea in mind, work

was undertaken in which larger aliquots than those recommended in Bulletin 31 were used. The results obtained by the use of larger portions of solution yielded, in general, more reliable figures. If larger quantities of solution were to be used, a great deal of the argument in favor of the colorimetric and turbidimetric procedures disappeared. The small portions of solution required for these methods have always been considered one of their great merits. In the soil extracts which contained the largest quantities of plant nutrients, if larger aliquots were taken, it was very clear that the ordinary volumetric and gravimetric procedures could be used. It then became important to learn whether the standard methods of determination could not be applied to the weaker solutions if a carefully standardized technic were adopted. In the work undertaken along this line the dilute and average solutions previously mentioned were used. As a result, it is believed that a more satisfactory procedure than the colorimetric has been developed for phosphates, calcium, and potash. The methods used are quite well known, but a great deal of work was done to establish the exact conditions for accurate results with the dilute solutions employed.

The description of the detailed procedures used follows.

PHOSPHATE.—Evaporate two portions of soil extract of 200 c. c. each in a 200-c. c. porcelain casserole. This size of casserole stands ignition excellently. Add a few drops of hydrochloric acid diluted 1 to 1 before the above solution reaches dryness to aid in decomposing soluble silicates. Ignite the dry residues in the casserole over a Meeker burner at a moderate temperature till a grayish white residue is obtained. Cool. Take up the residue with 10 c. c. of nitric acid diluted 1 to 9. Cover with a watch glass and digest on the steam bath for approximately 10 minutes to insure complete solution. Filter into a 200-c. c. Erlenmeyer flask. Wash the casserole with two more portions of 10 c. c. each of hot nitric acid diluted 1 to 9. Wash the dish, and filter with small portions of hot water. Keep the total volume of solution to about 50 c. c. Cool. Add a few drops of methyl orange indicator and neutralize rapidly with concentrated ammonia. Bring just to acid reaction with concentrated nitric acid. Add 2 c. c. of saturated ammonium nitrate. Place the flasks and a quantity of properly acidified ammonium-molybdate solution [1] in a water bath at 50° C. When all the solutions have reached this temperature, add 5 c. c. of molybdate to each determination. Keep at 50° C. for ½ hour. Remove from the water bath, and filter at once on prepared asbestos felts. Wash with cold distilled water till free from acid by the usual tests.[1] Transfer filter felt to the same flask, using approximately 25 c. c. of distilled water free from carbon dioxid. Add 15 c. c. of sodium hydroxid of which 1 c. c. is equivalent to 0.1 mgm. of phosphorus-pentoxid and observe carefully whether the solution of the yellow precipitate is complete. Titrate the excess alkali with hydrochloric acid of the same strength, using phenolphthalein as indicator. Calculate results to either elementary phosphorus or the phosphation, as desired.

CALCIUM.—Evaporate 200 c. c. of water extract to dryness in a 200-c. c. casserole. Ignite at a moderate temperature over a Meeker burner till a grayish white ash is obtained. This step is desirable to remove traces of organic matter, even though the

[1] WILEY, H. W., ed. OFFICIAL AND PROVISIONAL METHODS OF ANALYSIS, ASSOCIATION OF OFFICIAL AGRICULTURAL CHEMISTS, AS COMPILED BY THE COMMITTEE ON REVISION OF METHODS. U. S. Dept. Agr. Bur. Chem. Bul. 107 (rev.), p. 4. 1908. Reprinted in 1912.

extracts may be decolorized with carbon-black. Take up with 20 c. c. of hot distilled water acidified with hydrochloric acid diluted 1 to 1. Digest for a short time on the steam bath to insure total solution. Filter and wash the dish and the funnel with hot water. Do not permit the total volume of solution to exceed 50 c. c. Make faintly alkaline with ammonia, heat to boiling, add 5 c. c. of 10 per cent ammonium chlorid and 5 c. c. of saturated ammonium oxalate. Cover solutions with watch glasses, place on steam bath at moderate temperature (about 60° C.), and allow to stand overnight to insure complete precipitation. Filter on quantitative filter paper. Wash till free from chlorids, using successive small portions of hot water. Dissolve the precipitate in 50 c. c. of hot sulphuric acid diluted 1 to 4, receiving the acid and hot water subsequently used for washing the filter paper in the beakers used for precipitation. Titrate the hot solution with *N* 1/200 potassium permanganate, 1 c. c. of which is equivalent to 0.1 mgm. of calcium.

POTASH.—Measure 200 c. c. of water extract into a 200-c. c. casserole, acidify with 0.5 c. c. of sulphuric acid diluted 1 to 1, and evaporate to dryness on the steam bath. Heat gently on an asbestos hot plate and keep the casserole constantly in motion to prevent spattering until the excess of sulphuric acid has volatilized. Then ignite over a Meeker burner until a white or grayish white residue is obtained. Cool and take up the residue in successive small portions of hot distilled water. Filter through 5.5 cm. quantitative filter paper, using 30 to 40 c. c. of water. Acidify with three or four drops of hydrochloric acid diluted 1 to 1. Add 8 to 12 drops of platinic-chlorid solution and evaporate to a pasty consistency on the water bath; care should be exercised to avoid overheating. Cool. Take up the residue in 5 c. c. of 95 per cent alcohol, observe that an excess of platinic chlorid is present. Triturate the precipitate carefully with a rubber "policeman" and filter at once on a carefully prepared and weighed Gooch crucible. Wash with 95 per cent alcohol till the filtrate is colorless, then with 30 to 40 c. c. of ammonium chlorid, 100 gm. to 500 c. c. of water, which has been saturated with potassium platinic chlorid. Wash once with 80 per cent alcohol and then thoroughly with 95 per cent alcohol. Dry in an oven at 100° C. and weigh. Calculate the weight of potassium.

With the use of the known solutions previously prepared and the above methods, the following results (Table IV) are typical of the accuracy obtained.

TABLE IV.—*Analyses of dilute and average solutions by the methods used in this investigation*

Solution and treatment.	K.		Ca.		PO_4.	
	Theory.	Determined.	Theory.	Determined.	Theory.	Determined.
	P.p.m.	*P.p.m.*	*P.p.m.*	*P.p.m.*	*P.p.m.*	*P.p.m.*
Dilute solution (untreated)	1.2	1.05	1.50	1.62	1.0	1.12
	1.2	1.05	1.50	1.47	1.0	1.01
	1.2	1.21	1.50	1.65	1.0	1.20
	1.2	.97	1.50	1.60	1.0	.94
	1.2	1.00	1.50	1.45	1.0	1.10
	1.2	1.22	1.50	1.60	1.0	.97
Mean	1.2	1.08	1.50	1.56	1.0	1.06
Average solution (untreated)	6.0	6.05	7.5	7.91	5.0	5.06
	6.0	6.20	7.5	7.90	5.0	5.02
	6.0	6.05	7.5	7.62	5.0	4.90
	6.0	6.60	7.5	7.64	5.0	5.15
	6.0	5.95	7.5	7.66	5.0	5.10
	6.0	6.50	7.5	7.80	5.0	5.19
Mean	6.0	6.22	7.5	7.75	5.0	5.07
Percentage of error, dilute solution:						
Mean	.....	10.00	.....	4.00	.....	6.00
Maximum	.....	19.00	.....	10.00	.....	20.00
Percentage of error, average solution:						
Mean	.....	3.6	.....	3.00	.....	1.40
Maximum	.....	10.0	.....	5.40	.....	3.80

The determinations on each element are given on six duplicate portions of solution. In addition, the mean percentage of error is calculated, as well as the maximum error for any single determination. It will be observed that the agreement with the theoretical result is satisfactory for such dilute solutions. The potassium determination shows the greatest discrepancy, with a mean error of 10 per cent and a maximum of 19 per cent on the dilute solution. On the average solution the results are much closer, ranging from 3.6 to 10 per cent. With calcium the error on both the dilute and average solution is even smaller, 4.0 and 3.0 per cent for a mean result, and 10 and 5.4 per cent for a maximum. The phosphate determination shows a slightly larger fluctuation; in the dilute solution from 6 to 20 per cent, but the higher figure was only obtained in one analysis. The stronger solution gave greater accuracy than was obtained in any of the other work.

Taken as a whole, it is believed that the number of determinations is sufficiently large to show the small probability of the occurrence of the maximum error. The mean error will therefore be taken as the usual figure to be applied in the interpretation of the subsequent results. All data bearing on the seasonal studies which follow will be considered in the light of their accuracy as affected by the mean and maximum error.

EXTRACTION PROCEDURE

It has been pointed out in an earlier portion of this discussion that several extraction procedures have been applied to the study of the water-soluble material of soils. In Europe the methods of Schlœsing (*46*, *47*) and Mitscherlich (*42*) are largely favored, though the work of the U. S. Bureau of Soils (*61*) has some followers. This latter system of extraction is practically the only one which has been used in this country. The desire to have the result of this investigation somewhat comparable to previous work was therefore an argument in favor of this general procedure. This would not have held had there been any closer method of approximating the actual soil solution, for the medium which nourishes the plant should always be our final object. As before noted, it is not known that this actual solution has ever been obtained. It then becomes necessary to use some arbitrary method of extraction, and from the data at hand in beginning this work the general procedure of the U. S. Bureau of Soils was chosen.

In all the seasonal studies which are recorded later only fresh soil was used for the analytical studies. The great change which soil undergoes in drying as seen from the work of King (*35*), outweighs any considerations of expediency. King himself took the contrary view, but a study of his own figures shows how large and how variable were the changes between different soils caused by drying the samples previous to analysis. His adoption of this modification was influenced by a desire to carry on work at several stations from one central laboratory. In the present investigation the soils had been brought together, so no such reason existed. It has been desired throughout to perform all work on the fresh soils and to show what differences existed in them.

The uniform procedure of extraction is as follows:

Place the weighed portion of fresh soil in a large mortar and mix with a small amount of distilled water till it becomes a thin homogenous paste. Then add the rest of the distilled water, making in all five times the weight of the soil and mix the whole for exactly 3 minutes. Then transfer to wide-mouthed bottles all the solution and suspended soil that will pour off and allow it to stand for 40 minutes. At the end of this period pour the solution without mixing into cylinders of a Briggs filtering apparatus, connected to the pressure system, and apply compressed air at approximately 100 pounds' pressure till filtration is complete. Discard the first portion of the solution, about 50 c. c., to avoid any dilution by the moisture held in the Pasteur-Chamberland candles and also any small absorption by the filter from the solution.

After filtration is complete wash the filter candles and cylinders in tap water, rinse in distilled water, and pass 600 to 800 c. c. of distilled water through each candle to wash out any remaining portions of solution. After each weekly set of filtrations is completed, thoroughly dry the washed candles in an air oven at 100° C. to prevent the development of bacterial flora in the outer pores of the tubes. The efficiency of filtration of the candles is gradually impaired by continual use, owing to the deposition of clay and fine silt in the unglazed porcelain of which it is composed. This can be partly remedied by igniting the dried tubes in a muffle furnace for ½ hour or more.

Then cool the candles and pass distilled water through them to remove charred organic matter and salts formed by the process of ignition.

In the work carried out in 1915, with the analytical methods of the Bureau of Soils, 150 gm. of fresh soil constituted the sample treated with 750 c. c. of distilled water. In 1916 the modified procedure which has been described required a larger volume of solution. Accordingly 340 gm. of soil has been treated with 1,700 c. c. of distilled water. This volume of solution is the maximum quantity that can be filtered in two cylinders of the filtering apparatus. These two portions of solution are afterwards united and furnish a volume sufficient for the determination of phosphates, calcium, potash, nitrates, magnesium, and total solids, if desired. A moisture determination was in each case performed on the sample of fresh soil, and the result used in correcting the analytical data to bring it to a uniform basis.

In this connection it should be pointed out that the form in which the final results are to be stated is a matter of some importance. Mitscherlich (*42*), King (*35*), Whitney and Cameron (*61*), all expressed their results on the basis of percentage or parts per million of the dry soil. Gola (*18*), on the other hand, referred his to the concentration of the solution obtained, which he considered to be representative of the soil solution. Inasmuch as it is the soil solution which is our final object, it would be natural to refer the analytical results to the actual soil moisture determined in each sample. Desirable as it is, it is not believed that we possess the necessary information in regard to the state of the soil moisture to do this correctly. In discussing the results on the moisture equivalents given in Table II we have referred to the unfree water present in soils.

The work done by Briggs and Shantz (*8*) on the wilting coefficient of soils has shown the variations which occur among different soils, especially where they are of diverse types. Their work demonstrates clearly that a large amount of moisture is unavailable to the plant in soils which are high in colloidal material. Recently Bouyoucos (*4*) has called attention to the correlation which exists between the moisture held in unavailable form in the soil, as determined by the above method, and the unfree moisture determined by the dilatometer method. He has also compared the results obtained by these two procedures with the determination of the moisture which fails to freeze. A remarkable agreement is found to exist. Working with some 14 soils used in the present study Hoagland (*27*) has found that in all the silty clay loams a large percentage, varying from 13 per cent to 18 per cent, does not freeze. In the fine sandy loams the percentage is much smaller, from 4 per cent for soil 8 to 8 per cent for soil 10. The extent of these variations and their significance is discussed at greater length by Hoagland (*27*). If this moisture is held, either loosely chemically combined or physically absorbed or both, it is at least possible that it is not available

for the solution of the soil nutrients. In such a case the actual available solution carrying plant nutrients would not be very different in the complex silty clay loams from that which exists in the fine sandy loams. It has therefore been decided to express all results on the basis of the dry soil until further evidence is obtained as to the condition of the moisture in the soil.

AGREEMENT OF DUPLICATE EXTRACTIONS

Before the results obtained by any extraction procedure can be considered, it is necessary to know the limits of the accuracy which it is possible to achieve. The first important point in this connection is the possibility of obtaining accurate duplicate extractions. A number of sets of duplicate extracts have been made from samples of fresh field soils. The results on four typical soils, two silty clay loams and two fine sandy loams, are given in Table V. It will be observed that the agreement is well within the limits of the mean factor of error given in Table IV for all the elements except calcium. It will be remembered that the factor of error for this element ranged from 4 to 10 per cent. With the two fine sandy loams the variations between the two duplicates is between 10 and 15 per cent. This result would readily be accounted for by the solubility of the calcium compounds present in the soil and indicates that it is necessary to obtain far larger changes with this element than any others studied before the result can be considered significant. It must be emphasized, however, that duplicate results such as those given above can only be obtained if every step in the procedure chosen is carefully followed.

TABLE V.—*Typical duplicate extractions of silty clay loams and fine sandy loams*

[Results expressed as parts per million of dry soil. Ratio of soil to water 1:5]

Soil.	NO_3.	PO_4.	K.	Ca.	Mg.
No. 1 silty clay loam	32.5	4.3	33.8	16.7	10.3
Do	33.3	3.8	34.8	16.3	9.9
Mean	32.9	4.1	34.3	16.5	10.1
No. 5 silty clay loam	27.6	13.9	29.5	57.1	14.8
Do	29.0	13.3	30.0	63.0	15.0
Mean	28.3	13.6	29.7	60.0	14.9
No. 7 fine sandy loam	26.3	3.6	18.0	37.5	10.5
Do	26.3	4.2	18.6	42.0	11.4
Mean	26.3	3.9	18.3	39.7	10.9
No. 8 fine sandy loam	22.6	11.7	33.7	35.1	8.1
Do	22.2	10.6	30.6	30.0	8.5
Mean	22.4	11.1	32.1	32.5	8.3

EFFECT OF TEMPERATURE AND CARBON DIOXID

The next point to be investigated was the possible effect of comparatively rapid changes of temperature. This was an important consideration in studying fluctuations in soluble nutrients within a short period of time. Such fluctuations were found to occur. It was extremely desirable to know whether the change in solubility was due merely to the physical effect of the increased temperature or was a secondary influence due to increased activity of the bacterial flora. Such activity would result in the production of appreciable quantities of carbon dioxid and a possible increase in soluble soil compounds.

A series of studies were undertaken to investigate these various effects. A silty clay loam soil of excellent productivity was used. One container of this soil had been kept fallow all season; the other had grown a crop of barley. Both samples contained practically identical quantities of moisture, slightly below the optimum for this soil.

One portion of each soil was placed in a bacteriological incubator at 29° C. A second was kept in a refrigerator at 6° for two hours, a third was treated with carbon dioxid for 24 hours, a fourth was air dried at 20° for 48 hours, and a control portion was kept for 24 hours untreated. The results are given in Table VI.

TABLE VI.—*Effect of low temperature, increased temperature, air-drying, and carbon-dioxid on water-soluble nutrients*

[Results expressed as parts per million of dry soil]

Treatment.	No. 5A (Yolo silty clay loam, cropped).							No. 5B (Yolo silty clay loam, uncropped).						
	NO_3	PO_4	K	Ca	Total solids.	Volatile solids (loss on ignition).	Nonvolatile solids.	NO_3	PO_4	K	Ca	Total solids.	Volatile solids (loss on ignition).	Nonvolatile solids.
2 hours at 6° C.	70.7	17.5	39.9	83.3	472	195	277	139.5	20.5	52.8	103.9	676	291	385
2 hours at 29° C.	68.4	14.5	43.5	83.3	459	189	270	143.2	13.0	67.3	97.7	626	254	372
48 hours air-dry	62.3	22.9	37.9	68.3	547	319	228	127.2	22.4	49.7	70.3	751	404	347
24 hourscarbon dioxid at 15° C.	72.5	18.1	52.6	113.2	805	252	553	150.7	21.8	52.8	120.9	918	316	602
24 hours untreated at 15° C.	68.4	20.2	47.5	75.5	447	195	252	135.8	17.2	58.3	97.0	632	273	359

The data in Table VI must first be considered by applying the mean factor of error for the several determinations. This correction shows that the effect of the temperature treatments in the incubator and refrigerator has been negligible. It is therefore probable that sudden wide changes of concentration of water-soluble nutrients are due to other factors than changes in the solubility of plant food caused by temperature alone.

The air-drying to which the two samples were subjected was carried out at 20° C. without exposure to sunlight. It was consequently less

rigorous than the similar treatment which surface soil received in the field. Even so it is seen to have produced several striking changes. The nitrates and calcium are slightly decreased, but the greatest difference is observed in the total solids. Here we see a significant increase. This is further shown by the volatile solids to be entirely due to a gain in soluble organic matter. Such an increase in soluble organic materials would suggest that the effect of air-drying on the soil minerals would largely be of a secondary nature. Any cultivation or stirring into the soil mass of this air-dried portion of the soil would result in placing this soluble material in circulation in the soil solution. It would thus become available as food for the biological life of the soil, and may be one of the factors tending to produce the large liberation of nutrients after cultivation.

In the final treatment of the two soil samples carbon-dioxid gas was frequently passed through the jars containing the soil during the 24-hour period. This resulted in a striking liberation of soluble mineral compounds. There was also a slight increase in the production of nitrates in comparison to the untreated soil, but it is very noticeable that the phosphates remained practically constant. This is significant. It will be pointed out later that phosphates are the only one of the plant foods with which the solution of each individual soil appears to be saturated. The amount of nonvolatile solids liberated by this treatment is over 200 p. p. m., and shows that the effect of the carbon dioxid extends to other compounds than those indicated. From this study it seems probable that the effect of the carbon dioxid present in the soil air and dissolved in the soil solution is the most important influence that renders the soil minerals soluble.

NATURE OF THE WATER EXTRACT

The above series of results establish the accuracy of the extraction procedure which has been employed. They do not throw any light on the nature of the solution obtained. All of the minerals present in the soil possess a small but appreciable solubility. Any soil extract will therefore contain not only the material which is actually in solution or very readily soluble but also an extra amount derived from the soil minerals themselves. This latter portion of the soil extract may in some cases be different for the same soil. It is a well-known principle that when a compound is treated with a solution containing a common ion its solubility will be repressed. If we now turn to the graphs showing the nutrients extracted from the same soils, cropped and uncropped (fig. 3–6), it will be observed that there are striking differences, which will be discussed later. In the cropped soil there is much less soluble material, and the solution used to extract it will more nearly approach distilled water than in its duplicate, where nothing has been removed by the

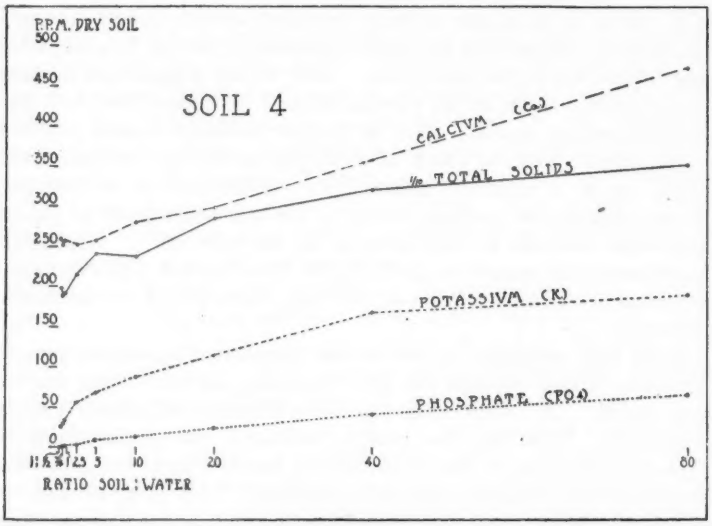

FIG. 3.—Graphs of the nutrients extracted from soil 4 by varying the ratios of soil to water. Calculated to parts per million of dry soil.

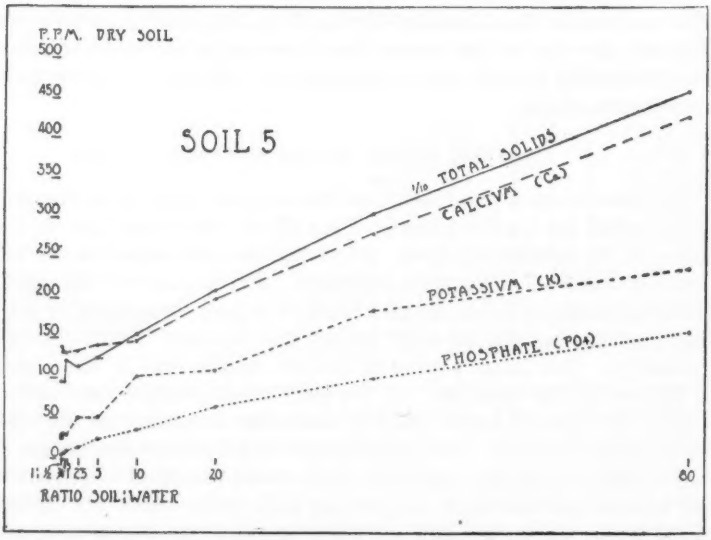

FIG. 4.—Graphs of the nutrients extracted from soil 5 by varying the ratios of soil to water. Calculated to parts per million of dry soil.

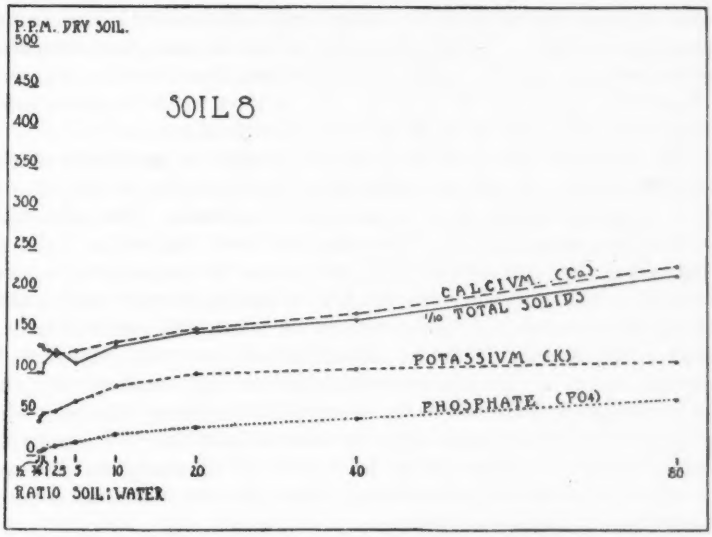

Fig. 5.—Graphs of the nutrients extracted from soil 8 by varying the ratios of soil to water. Calculated to parts per million of dry soil.

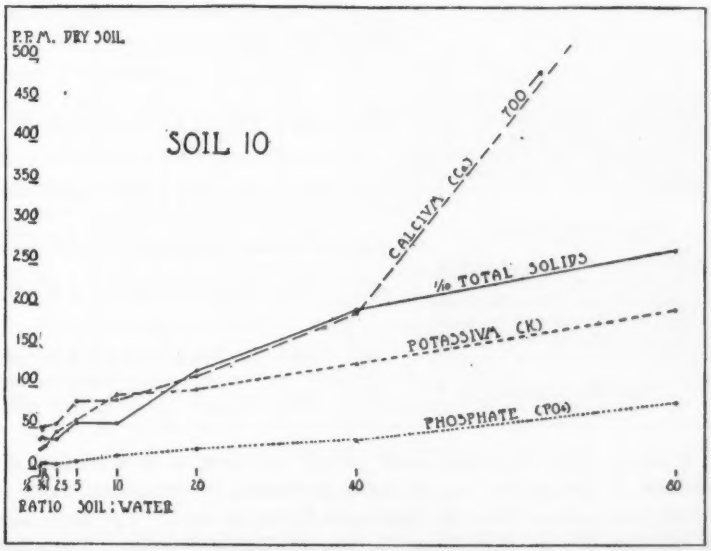

Fig. 6.—Graphs of the nutrients extracted from soil 10 by varying the ratios of soil to water. Calculated to parts per million of dry soil.

plant. It may therefore be expected that in the solution from this soil more material derived from the soil minerals will be soluble than in the uncropped extract. The effect of this will be to make the differences which actually exist less striking and evident than is really the case. The evidence given by the freezing-point method, which has greatly developed the above theory, is discussed by Hoagland (*27*).

The suggestion was made by Burd that it might be possible to obtain some conception of this repressive effect by extracting a cropped soil with a diluted extract from its uncropped duplicate. Two soils were used for this purpose: Soil 5, Yolo silty clay loam, and soil 10, Tejunga fine sandy loam. In each case an extract was first prepared of an uncropped reserve portion of the soil and of another portion upon which a crop had been grown. A determination of total solids was immediately made. The solution from the uncropped soil was then diluted with distilled water, so that this solution added to that obtained from the weaker cropped soil would again be equal to the strong solution. The cropped soil was extracted with this diluted solution. The results of this extraction are compared in Table VII with the amounts obtained by the usual treatment with distilled water plus the quantities already present in the diluted extract.

TABLE VII.—*Extraction of two cropped soils with diluted extracts from duplicate bin soils*

[Results expressed as parts per million of dry soil]

Soil.	Total solids.	Fixed solids.	Volatile solids.	PO^4.	Ca.	Mg.	K.
Cropped soil 5 extracted with dilute extract from reserve bins...	1,686	724	962	15.4	187.0	41.5	66.1
Nutrients extracted from same soil by distilled water (1:5) + nutrients contained in the dilute extract.....	1,575	1,163	412	25.7	195.0	46.4	81.6
Depression of solubility.....	.....	439	.....	10.3	8.0	4.9	15.5
Cropped soil 10 extracted with dilute extract from reserve bins...	426	157	269	8.8	32.1	6.6	55.4
Nutrients extracted from same soil by distilled water (1:5) + nutrients contained in the dilute extract.....	589	298	291	16.4	55.8	8.8	76.8
Depression of solubility.....	163	141	22	7.6	23.7	2.2	21.4

With the Yolo silty clay loam 5 there was seen to be a distinct depression of phosphates and a slight depression of potassium, both of which were greater than the maximum factor of error. The depression of calcium was no more than the average factor of error. The effect was especially seen in the amount of fixed solids which was held out

of solution, but the total solids were slightly increased as organic matter replaced the nonvolatile solids.

With Tejunga fine sandy loam 10 there was a distinct depression throughout. Both solids and all individual constituents were decreased in quantity.

This evidence, together with that obtained by Hoagland (*27*) using the freezing-point method, clearly showed that the differences which may be found between cropped and fallow soils by the extraction procedure was always less than that which actually exists.

In the same paper (*27*) Hoagland has also shown, both by special extraction studies and by calculation from the amounts of total solids contained in the 1-to-5 extract, that the relation of the actual soil solution to this water extract is extremely close. The amounts of material in the 1-to-5 extract are approximately two to five times as great as in the soil solution. The range of concentration shown by these extractions is therefore undoubtedly too high. This does not nullify the differences between cropped and uncropped soils which are shown to exist by this procedure. Hoagland's results show that, if anything, these differences are actually much greater. A decrease in the range of concentrations would therefore have no more effect than to change the scale upon which the seasonal curves have been drawn.

EFFECT OF VARYING THE PROPORTION OF SOIL AND WATER

It was important to learn what relation the conventional 1-to-5 extract bears to other possible ratios of soil and water. Reference has been made to the work of Mitscherlich (*42*), in which he employed a series of varied extractions of soil with water saturated with carbon dioxid. This idea was now applied. Four soils, two silty clay loams and two fine sandy loams, were extracted with proportions of soil to water varying from 1 part of soil to ½ part of distilled water up to 1 part of soil to 80 parts of distilled water.

The results in parts per million of dry soil have been plotted in figures 3 to 6. It will be observed that with each soil the proportions of compounds extracted in the lower ranges of concentration were essentially the same. It was not until a range of concentrations of soil to water greater than 1 to 10 were reached that a distinct change in the extraction of nutrients took place. These results therefore warranted the employment of the 1-to-5 extract as a conventional procedure.

SEASONAL STUDIES OF THE WATER EXTRACT

FIRST SEASON, 1915

In the first season's work, in 1915, both containers of each soil were sown to barley. Half of the soils were planted on June 14, and the remainder one week later. At the same time the first soil samples were

taken with the 18-inch cheese trier previously mentioned. From 9 to 12 triers of soil were required for a sample of approximately 600 gm. The holes left by removing these samples were filled with reserve soil from the bins.

It was felt that this procedure might be open to some objections, owing to the fact that the soil in the bins was partially air-dried. In any one season 10 sampling periods is the maximum number, and the amount removed would not exceed 6 kgm. This amount was less than 0.8 per cent of the total soil present. The error involved was therefore smaller than it was possible to detect by any available methods.

In order to minimize this influence, the containers were always sampled by a definite system, so that no two samples were taken from the same spot twice in the same season. The process of sampling was performed with great care. There was no breakage of plants and no evidence of injury from the small roots cut by the cheese trier. The growth obtained has been extremely satisfactory, both in height and vigor. The plants were spaced at the usual field distance, 6 inches apart each way. In 1915 one seed was planted in a place, and a small number of extra seeds were started simultaneously in the same soil. These extra plants were then transplanted into any spaces where the seed failed to sprout. An even stand was obtained in all except two duplicate containers, soils 3 and 5. The following season the writers were able to obtain a perfectly uniform growth by planting three or four seed in each place, and then thinning to one plant of average size. The seed used was furnished by the Division of Agronomy and was a pure strain of Beldi barley. Before planting, it was treated with formalin to prevent smut; seed of uniform size were selected.

A slight difficulty has been experienced toward the close of each season from the tendency exhibited by the crops on several soils to lodge. This has been corrected by a system of supporting wires.

In 1915 the crop matured, and was harvested from October 21 to November 6. This was a later date than commercial grain crops are grown in California, but it is believed that the results were strictly comparable among themselves. The crop yield is given in Table VIII and is expressed as total air-dry crop and grain in grams. The grain is also calculated as pounds and bushels per acre. It will be observed that in all the soils except No. 3 and 5 the agreement of the duplicates was excellent. These two soils, it will be remembered, were those in which the growth was least uniform.

TABLE VIII.—*Crop yield of 1915*

Soil.	Total yield of air-dry grain and straw.	Grain.	Grain (pounds per acre).	Grain (bushels per acre).	Variation from maximum yield of grain.	Difference between duplicates.
Yolo silty clay loam:	*Gm.*	*Gm.*			*Per cent.*	
No. 1A	2,092	730	5,614	93.6	11.7	0.0
No. 1B	1,904	730	5,614	93.6	11.7	.....
No. 2A	2,038	605	4,653	77.5	26.9	6.8
No. 2B	1,649	548	4,215	70.3	33.7	.....
No. 3A	1,421	474	3,646	60.8	42.6	17.1
No. 3B	1,083	333	2,561	42.7	59.7	.....
No. 4A	1,331	534	4,106	68.5	35.4	9.1
No. 4B	1,187	459	3,530	58.8	44.5	.....
No. 5A	1,863	529	4,069	67.8	36.0	13.2
No. 5B	1,742	420	3,230	53.8	49.2	.....
Yolo clay loam:						
No. 6A	2,287	739	5,684	94.7	10.7	4.0
No. 6B	2,182	705	5,422	90.4	14.7	.....
Hanford fine sandy loam:						
No. 7A	1,115	432	3,323	55.4	47.7	8.4
No. 7B	1,059	363	2,792	46.5	56.1	.....
Fresno fine sandy loam:						
No. 8A	2,136	827	6,361	106.0	.....	.....
No. 8B	2,022	780	6,000	100.0	5.7	5.7
Kimball fine sandy loam:						
No. 9A	1,066	388	2,984	49.7	53.1	2.1
No. 9B	1,096	405	3,115	51.9	51.0	.....
Tejunga fine sandy loam:						
No. 10A	1,401	495	3,807	63.5	40.1	0.6
No. 10B	1,337	500	3,846	64.1	39.5	.....
Madera fine sandy loam:						
No. 11A	2,020	742	5,707	95.1	10.3	3.9
No. 11B	2,194	774	5,953	99.2	6.4	.....
Arnold fine sandy loam:						
No. 12A	796	242	1,862	31.0	70.8	3.4
No. 12B	775	214	1,646	27.4	74.2	.....
Standish fine sandy loam:						
No. 14A	1,364	390	3,000	50.0	52.8	1.6
No. 14B	1,359	403	3,100	51.7	51.2	.....
Average variations between duplicates	.....	.....	.....	.....	.....	5.8

In order to compare the two seasons' crops on a uniform basis and also to allow for the mean and maximum difference in duplicates, all results of the yield of grain have been calculated to the percentage of variation from the highest yield. The figures given for the duplicate containers have been substracted and expressed in a separate column. The difference between soils 3A and 3B was the maximum, amounting to 17.1 per cent, while that of soils 5A and 5B was 13.2 per cent. The mean figure given by the above was 5.8 per cent. These differences have been expressed diagrammatically in figure 7. Here it is seen that, by taking the maximum variation between duplicates as the standard, soils 8, 11, 6, and 1 have practically an equally high production. Soil 2 is significantly lower, and the others range lower, down to soil 12.

In figures 8 to 20 it is seen that the graphs given on the duplicate containers agree excellently. In all the soils except No. 9, 12, and 7 there was an appreciable increase of potassium, which occurred from four to six weeks after the time of planting. In all except the same soils, and in addition No. 14, there was a liberation of nitrates which, like the potassium, began to fall soon after the crop was rapidly developing.

The method employed for calcium had proved so inaccurate that the results were excluded from the final charts. It was known that the potassium method had a high factor of error in the lower concentrations. A definite increase of nitrates had been shown in the earlier periods of growth. It was very clear that before any interpretation of these figures could be made it was necessary to have not only more accurate methods

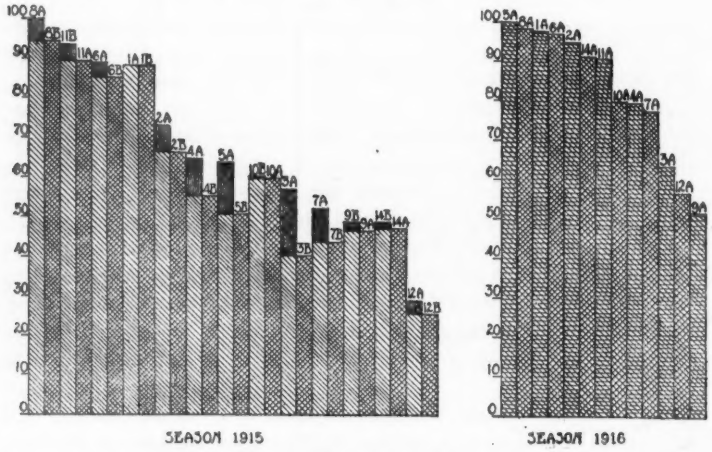

FIG. 7.—Graphs of the yield of grain in 1915 and 1916, expressed as a percentage of the maximum yield. The heavily shaded portions in 1915 represent difference between duplicates.

of determination but also a comparison between the conditions which were found in the planted soil and those which would have occurred in the same soil had the crop not been present.

The first season's work therefore established the following facts: (1) That a satisfactory duplicate crop could be grown under the conditions employed; (2) that the extraction technic followed yielded practically duplicate graphs for the elements extracted. The period of a year's treatment under uniform conditions had also tended to bring the soils into normal relation to each other. It had given an opportunity for the soils to recover from the sifting and handling which they had received and be more comparable to a varied group of field soils exposed to the same climatic conditions.

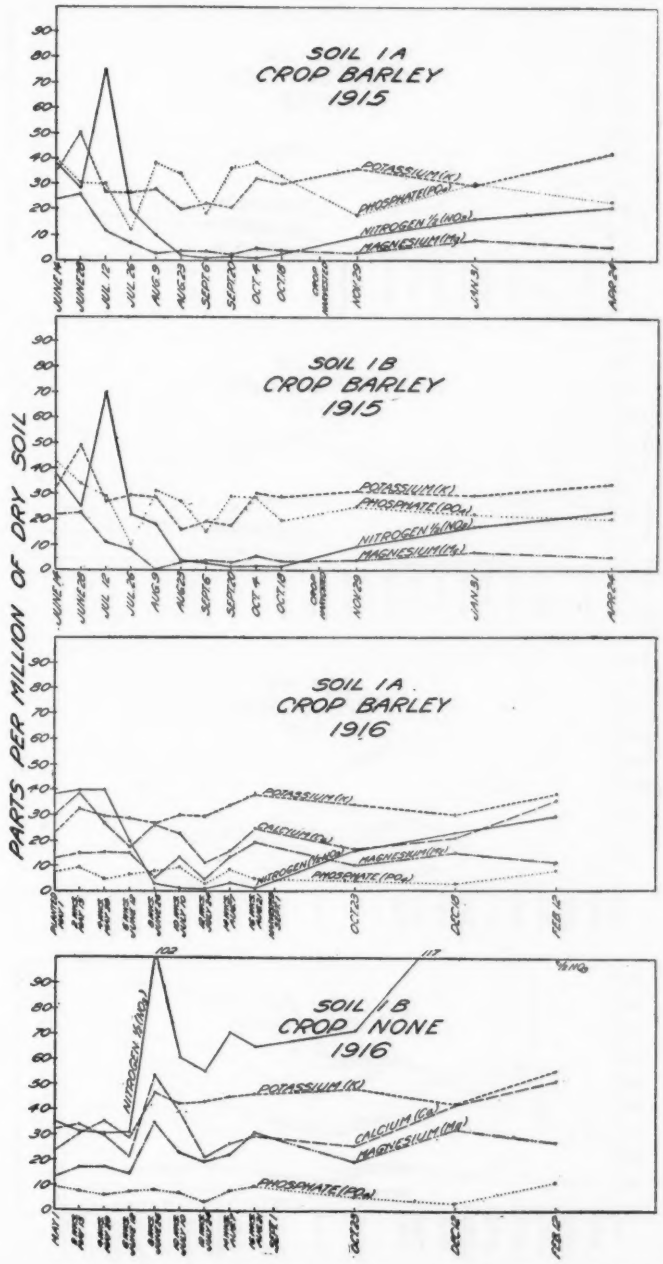

FIG. 8.—Graphs of the seasonal studies of the water extract of soil 1, Yolo silty clay loam.

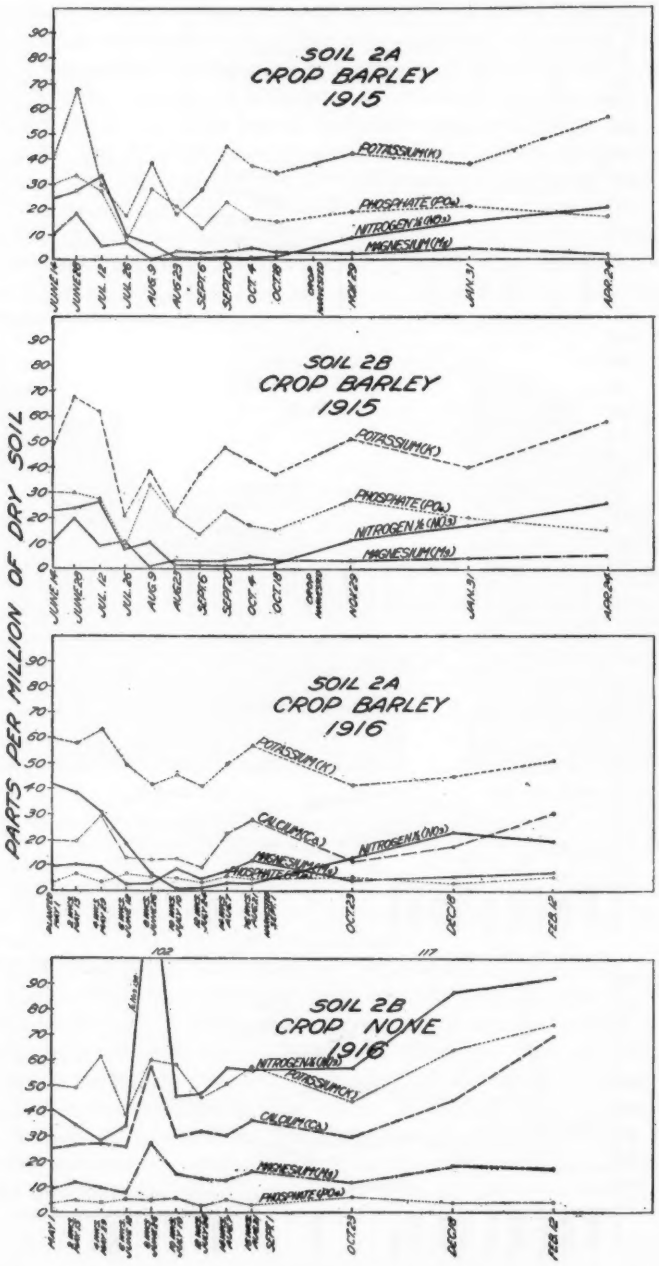

FIG. 9.—Graphs of the seasonal studies of the water extract of soil 2, Yolo silt clay loam.

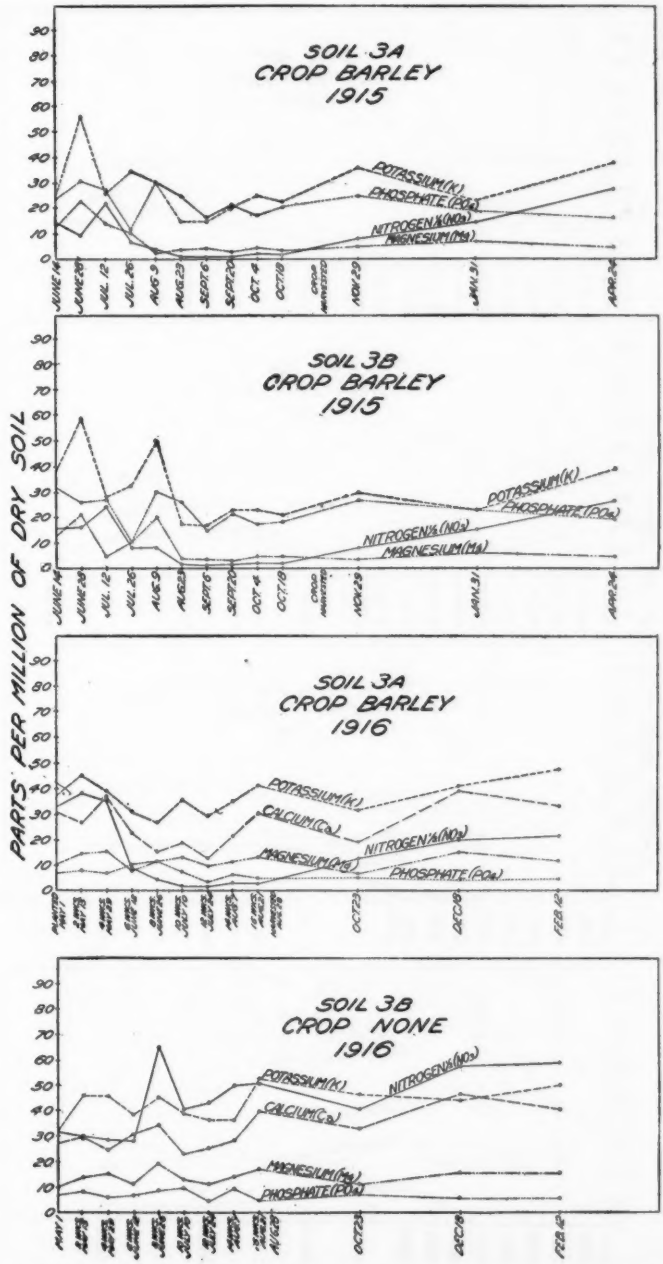

FIG. 10.—Graphs of the seasonal studies of the water extract of soil 3, Yolo silty clay loam.

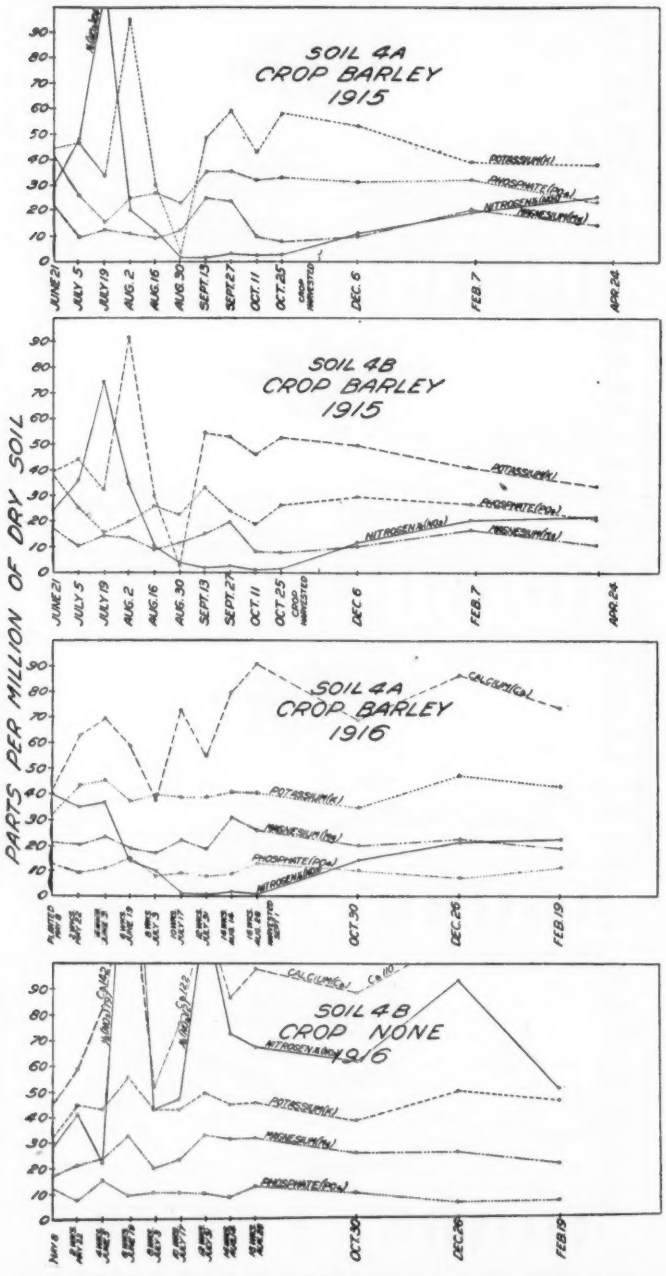

FIG. 11.—Graphs of the seasonal studies of the water extract o fsoil 4, Yo'o silty clay loam.

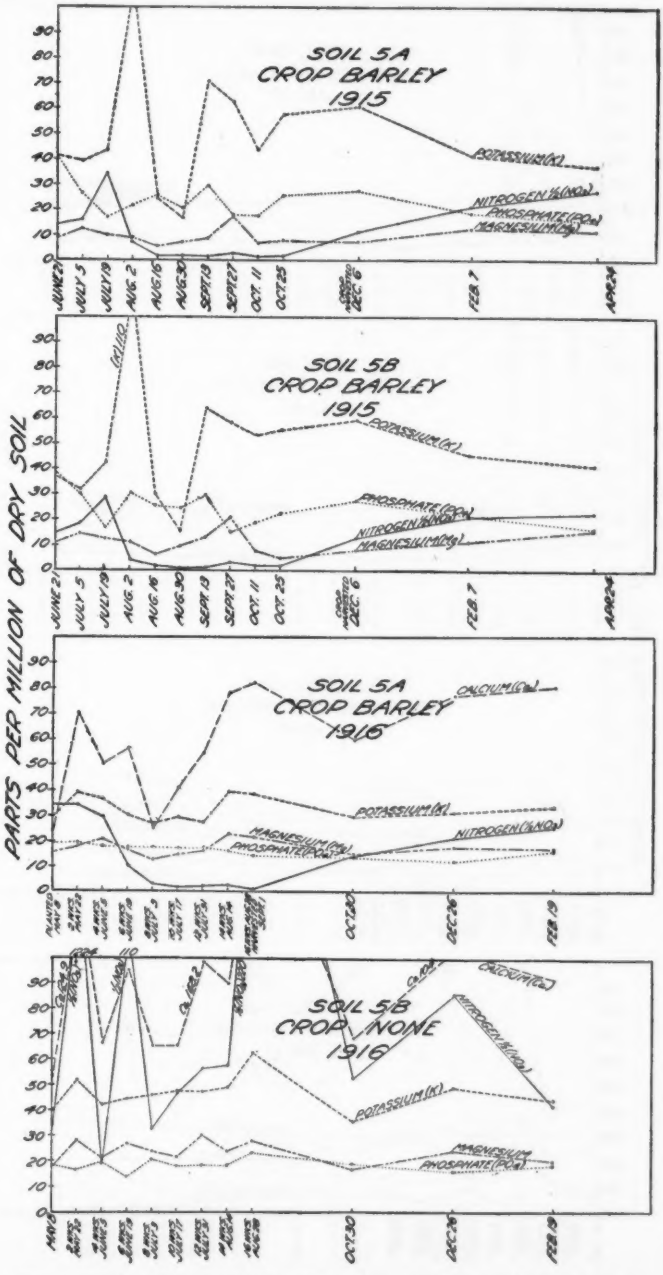

FIG. 12.—Graphs of the seasonal studies of the water extract of soil 5, Yolo silty clay loam.

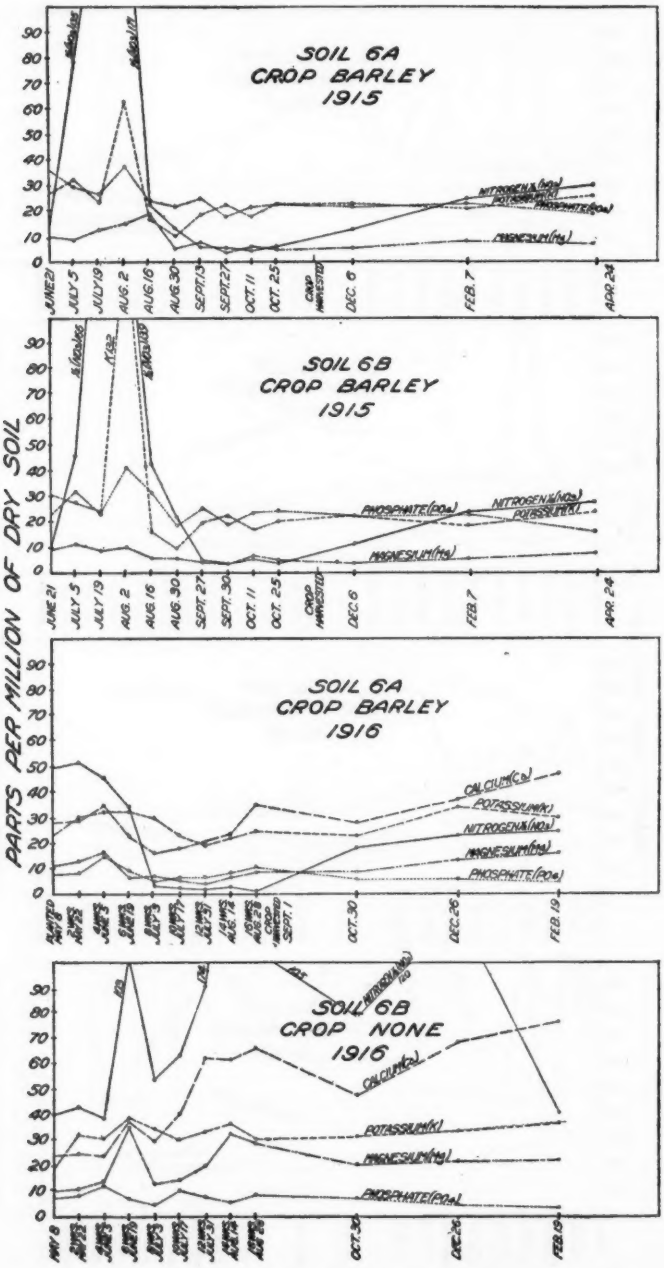

FIG. 13.—Graphs of the seasonal studies of the water extract of soil 6, Yolo clay loam.

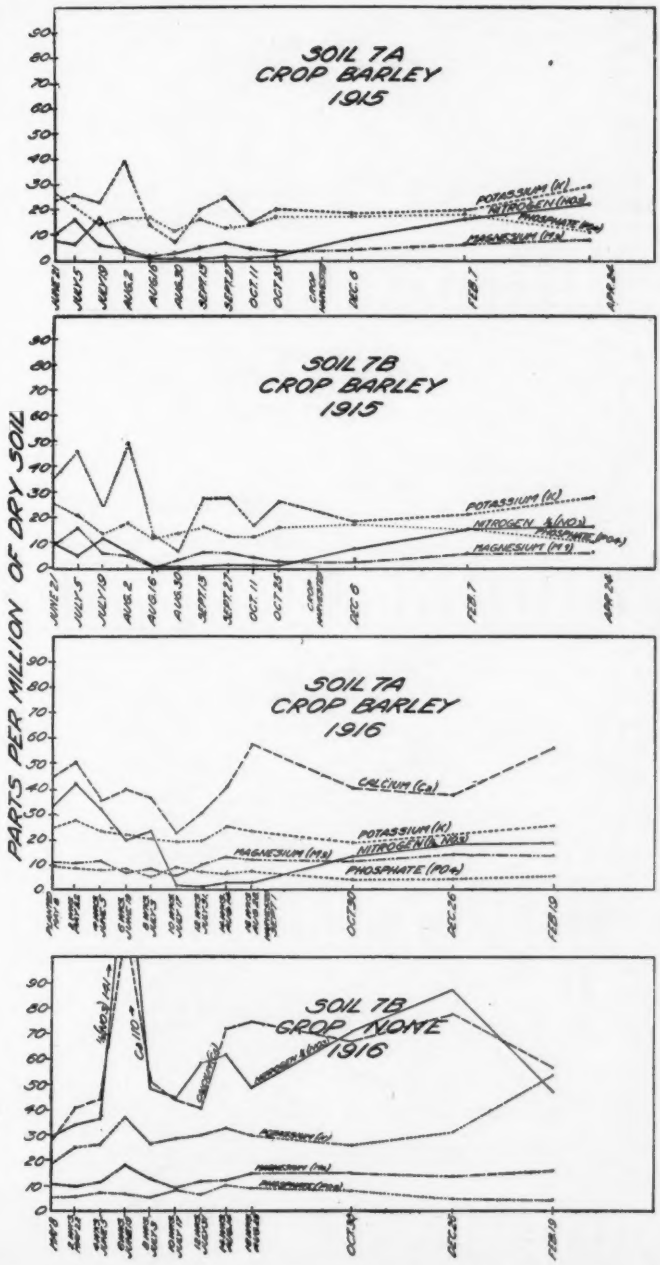

FIG. 14.—Graphs of the seasonal studies of the water extract of soil 7, Hanford fine sandy loam.

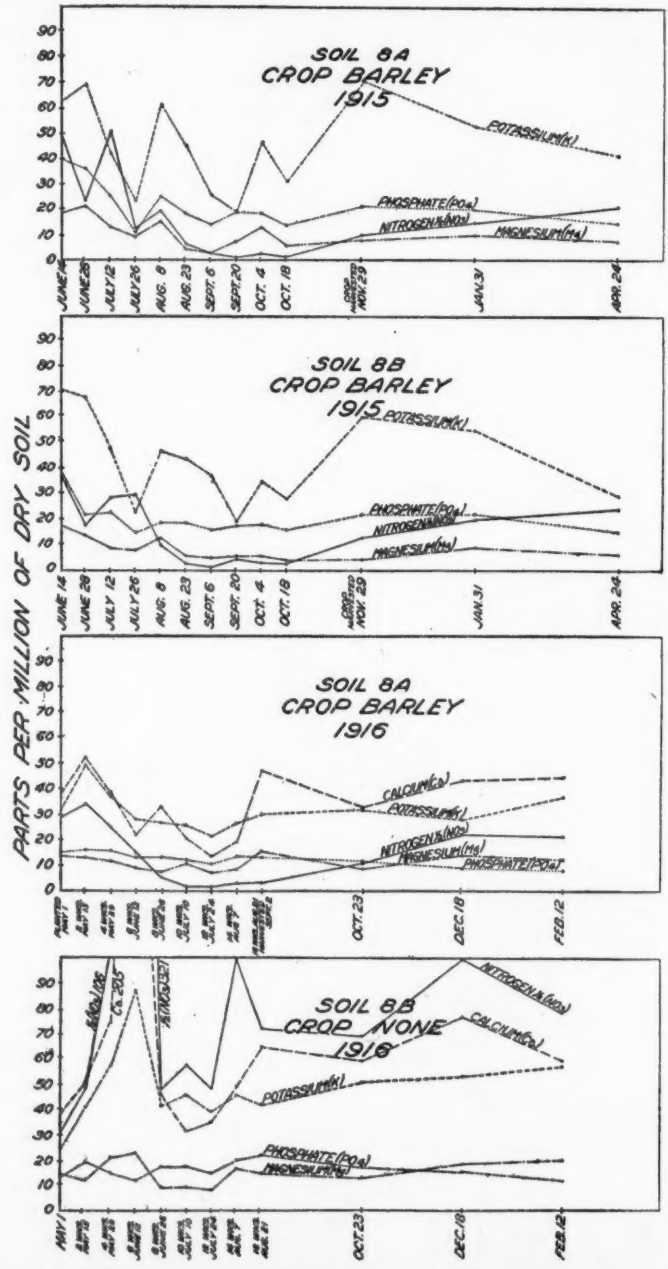

FIG. 15.—Graphs of the seasonal studies of the water extract of soil 8, Fresno fine sandy loam.

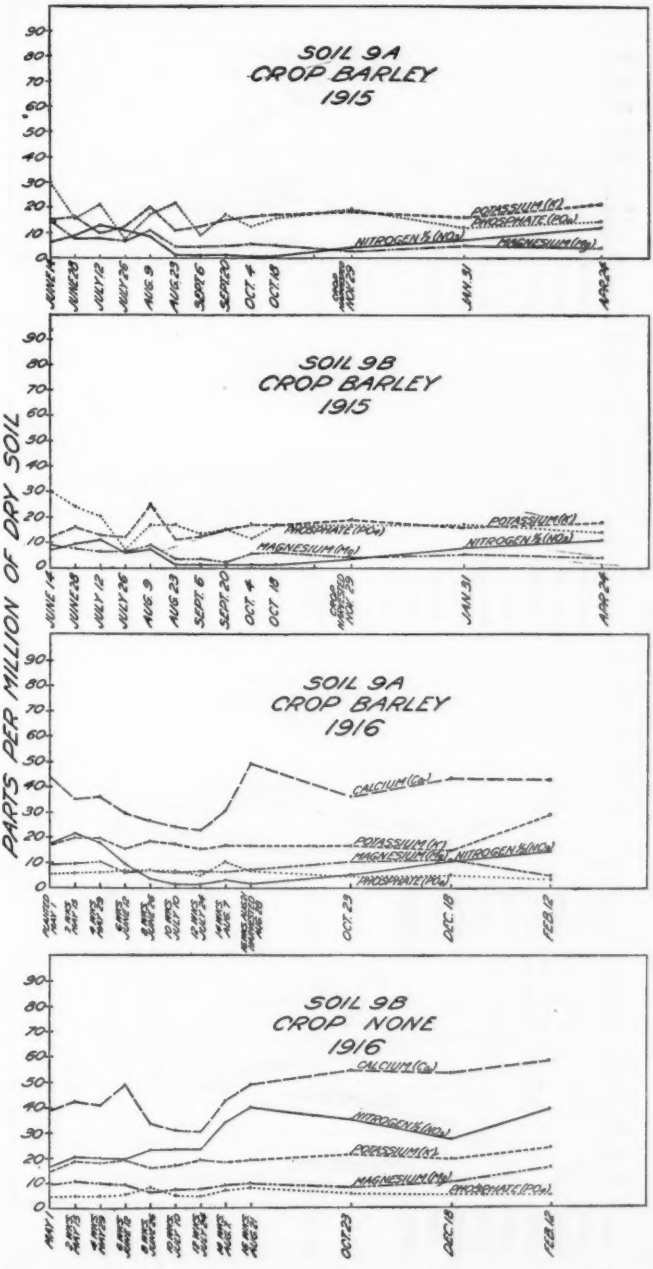

FIG. 16.—Graphs of the seasonal studies of the water extract of soil 9, Kimball fine sandy loam.

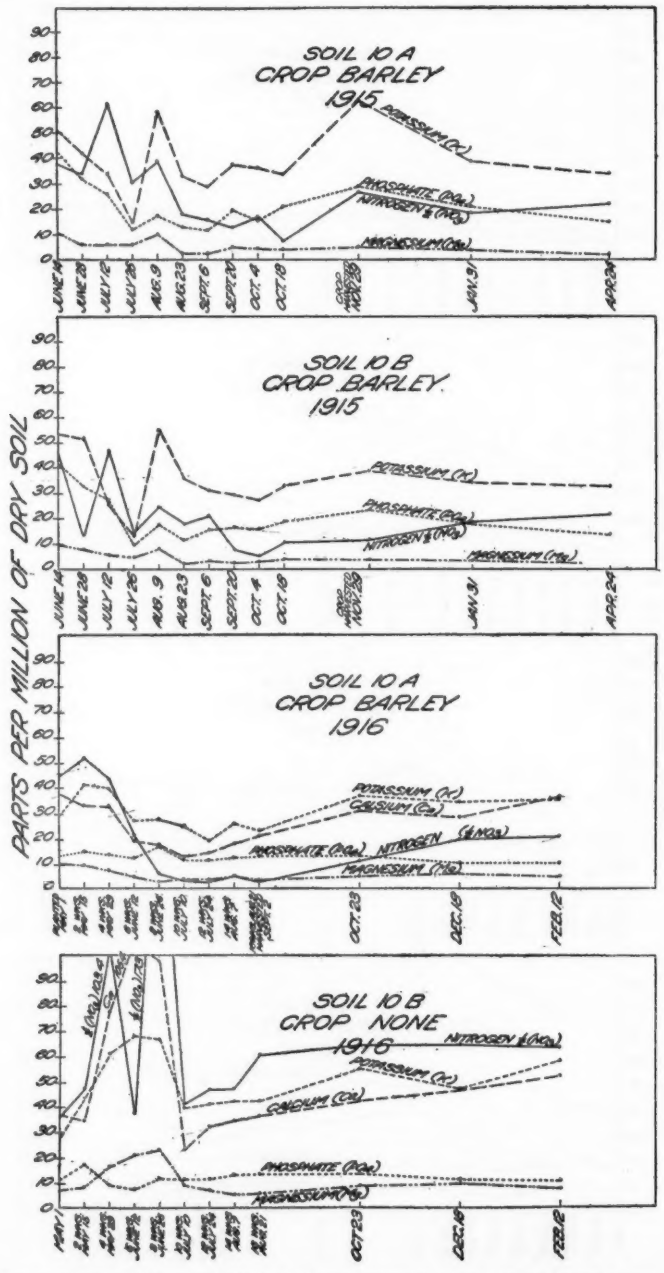

FIG. 17.—Graphs of the seasonal studies of the water extract of soil 10, Tejunga fine sandy loam.

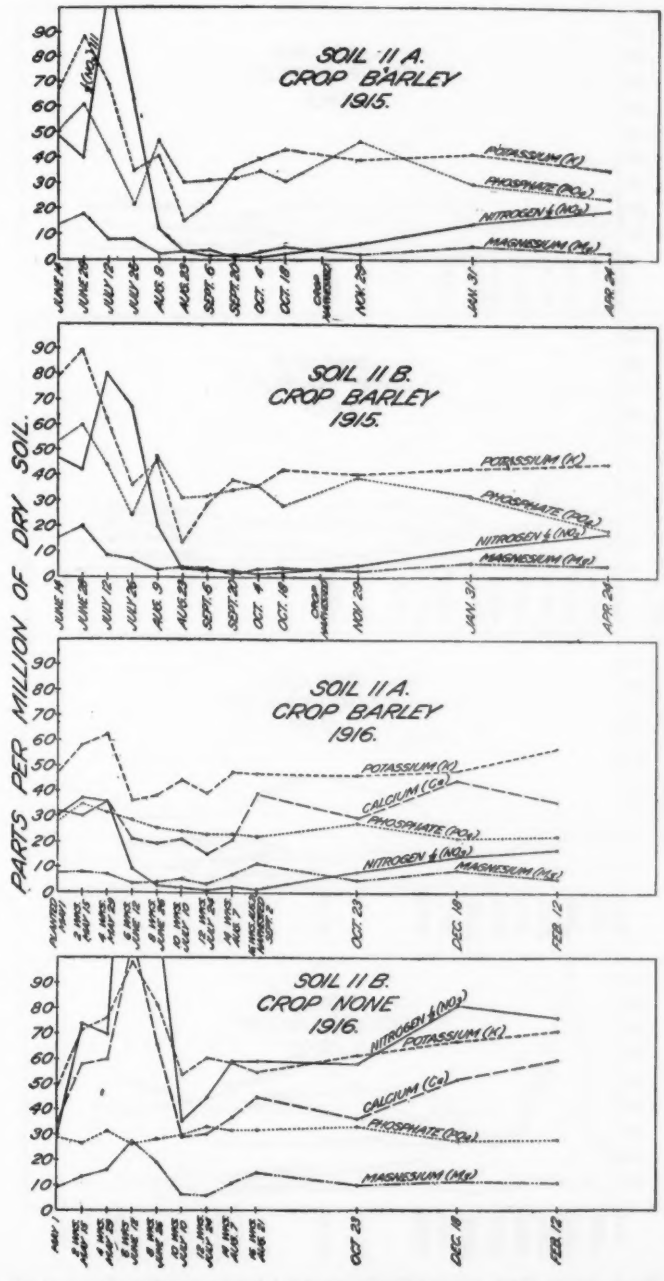

FIG. 18.—Graphs of the seasonal studies of the water extract of soil 11, Madera fine sandy loam.

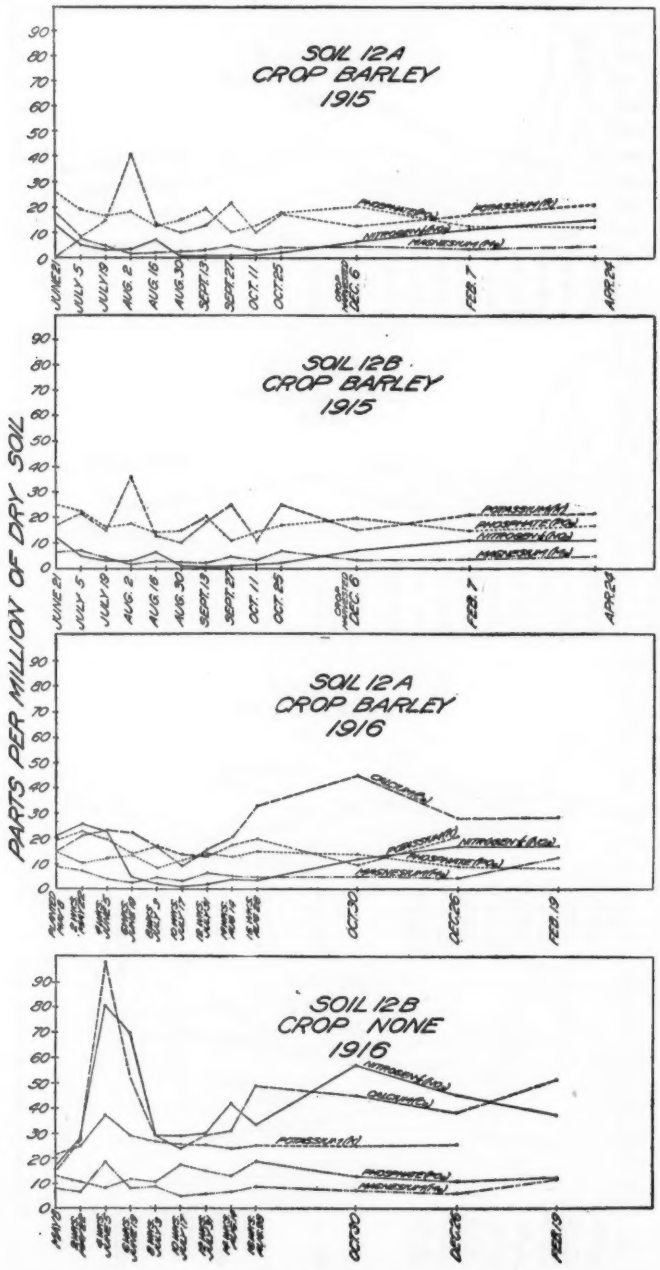

FIG. 19.—Graphs of the seasonal studies of water extract of soil 12, Arnold fine sandy loam.

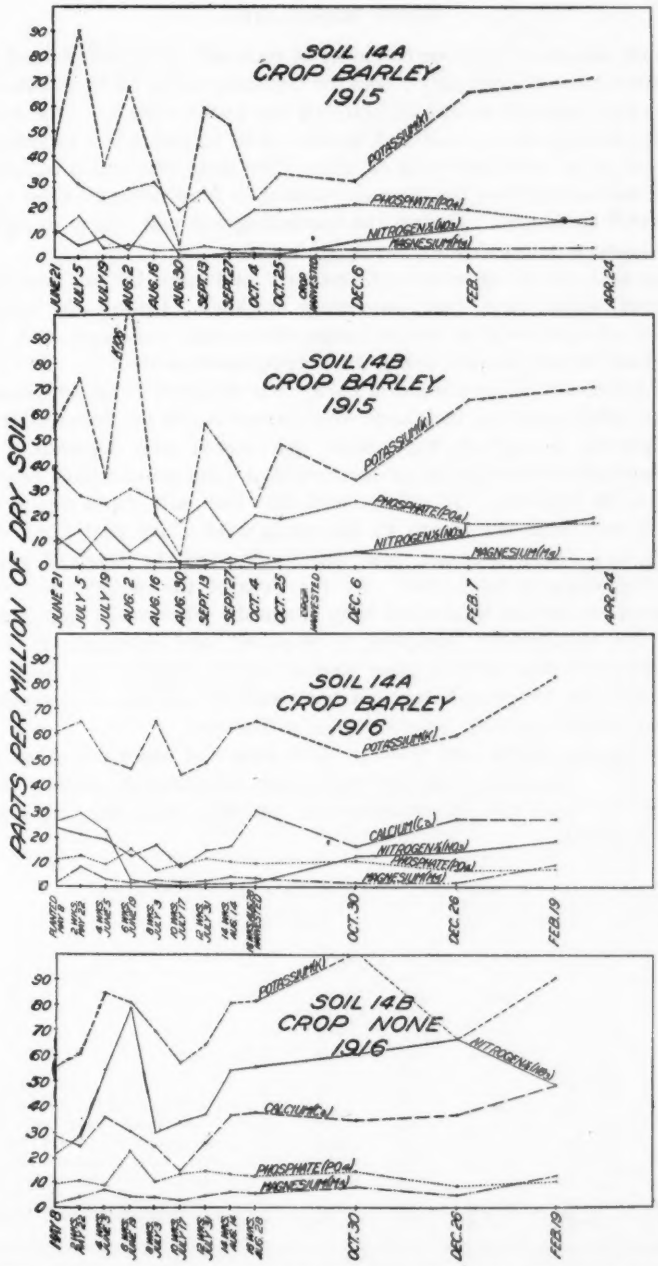

FIG. 20.—Graphs of the seasonal studies of the water extract of soil 14, Standish fine sandy loam.

SECOND SEASON, 1916

In the season of 1916 one container of each soil was again planted to the same strain of Beldi barley, and the duplicate was at all times treated in the same manner, except that no crop was grown upon it. One week before planting, the top soil to a depth of 8 or 10 inches was forked up and put in an excellent state of tilth. The soils were again sampled every two weeks from the time of planting in May until the crop was harvested in August. During the succeeding fall and winter samples were taken at approximately 8-week intervals.

The analyses of the water extracts were performed by the modified methods which have been previously outlined. During the latter portion of the sampling season cooperative work was performed by Hoagland on the samples, using the freezing-point method.

An extremely uniform stand of barley was obtained in all containers. Shortly after sprouting, the plants were thinned to one vigorous seedling. The growth throughout the season was steady and vigorous. A diagrammatic representation of the height at each soil-sampling period is given in figure 21. It will be seen that the most rapid period of growth was from the fourth to the tenth week. By that time the plants had almost attained their full height, and the heads of grain were beginning to be formed. At the close of the twelfth week the maximum growth in height had been attained. Five weeks' additional time was required for complete development and ripening. It was interesting to note that in these studies, where moisture was never a limiting factor, the growth in height was extremely uniform, even though the dry matter produced did show great differences.

The results of the crop yield in total crop and grain are given in Table IX. The grain yield has again been calculated to pounds and bushels per acre, and the percentage of variation from the maximum yield is shown.

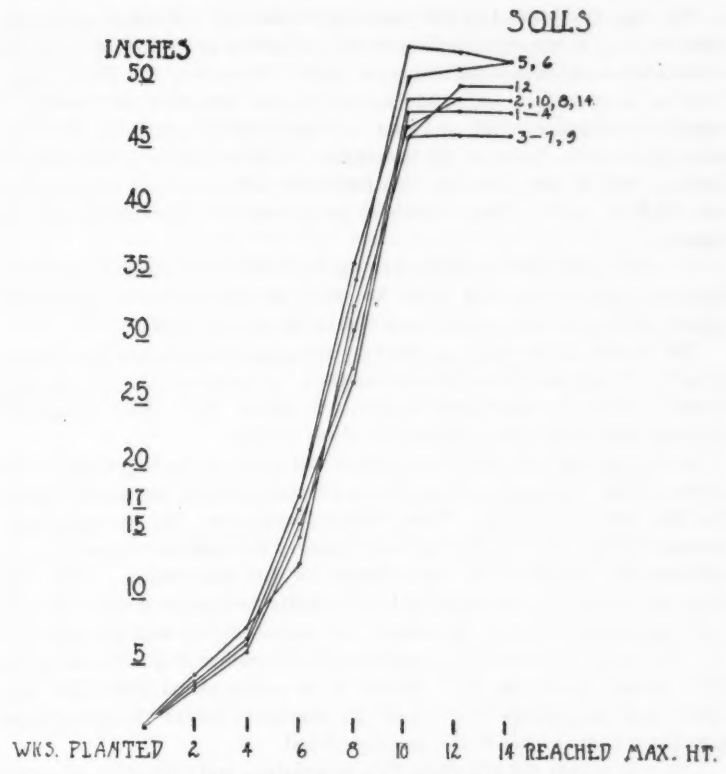

FIG. 21.—Graphs of the growth of crops in height, season of 1916.

TABLE IX.—*Crop yield in 1916*

Soil.	Total yield of air-dry grain and straw.	Grain.	Grain (pounds per acre).	Grain (bushels per acre).	Variation from maximum yield of grain.
Yolo silty clay loam:	*Grams.*	*Grams.*			*Per cent.*
No. 1A	1,474	675	5,192	86.5	2.2
No. 2A	1,530	655	5,038	84.0	5.0
No. 3A	970	439	3,377	56.2	36.4
No. 4A	1,252	549	4,223	70.4	20.4
No. 5A	1,652	690	5,307	88.4	.0
Yolo clay loam, 6A	1,523	670	5,153	85.9	2.8
Hanford fine sandy loam, 7A	1,414	541	4,161	69.4	22.5
Fresno fine sandy loam, 8A	1,719	679	5,222	87.0	1.6
Kimball fine sandy loam, 9A	946	357	2,746	45.8	48.2
Tejunga fine sandy loam, 10A	1,266	551	4,238	70.6	20.1
Madera fine sandy loam, 11A	1,547	625	4,807	80.1	9.4
Arnold fine sandy loam, 12A	970	390	3,000	50.0	43.4
Standish fine sandy loam, 14A	1,464	630	4,846	80.8	8.6

The figures obtained in the preceding season for the mean and maximum variation between duplicates will be used in order to find what will constitute a significant difference in yield. By taking the mean variation as the standard, soils 5A, 8A, 1A, 6A, and 2A are to be considered equally productive, while 11A and 14A are slightly lower. If, however, the conservative figure of the maximum variation between duplicates is used, it will be seen that No. 11A and 14A will also fall in the group of the highest yield. These relations are presented diagrammatically in figure 7.

It will be seen that six soils were significantly lower than the group of highest productivity. Of those No. 10A, 4A, and 7A were practically equal, while 3A, 12A, and 9A were distinctly low in yield.

The results of the water extractions are again presented in the form of graphs. In figures 8 to 20 the plot marked "A" is in each case the planted portion, while the uncropped duplicate is called "B." Some extremely striking differences are exhibited by these graphs.

In the planted soils the water-soluble nutrients at the beginning of the season, either remained on practically the same level or increased slightly for the first four weeks. Then, without exception, the nitrogen commenced to decrease rapidly and was followed in a smaller degree by the calcium and potash, and very slightly by the magnesium. The contrast shown by the unplanted soil was equally uniform in nature, though variable in the extent of the effect. In almost all the soils the effect of the cultivation was to cause a considerable liberation of soluble nutrients and, though there was later shown to be a depression from this high figure, yet the general range of all the nutrients except the phosphates continued to be higher in the uncropped soil.

The soils which did not show this stimulation and liberation of nutrients were No. 3B, 9B, and 12B. These were the least productive soils of the group and also had the lowest range of soluble nutrients.

It is extremely significant that this same period of high soluble nutrients in the uncropped soils corresponds to the period of lowered nutrients in the cropped duplicates. It was also the period, as may be observed in figure 21, in which the plants were making their most rapid growth.

The one compound which did not exhibit this liberation of excess nutrients in the uncropped soil was the phosphate. There were large differences between the amounts present in various soils, but for any one soil the amount was practically constant in the cropped and uncropped plot. It was the only soil nutrient studied which behaved in this manner.

All the above differences between the planted and unplanted soils which have been noted are greater than can be accounted for by the probable factor of error which has been determined in an earlier portion of the study. The maximum figure for any nutrient in the concentration found is 10 per cent, and that applies only to potassium and calcium. On applying this correction plus or minus to the periods of greatest de-

pression, it is clear that this will not account for the differences noted. With phosphates the probable maximum is 4 to 6 per cent, while with magnesium it would vary from 6 to 10 per cent. All these corrections fail to change significantly the figures recorded.

At two periods during the season of 1916 daily studies of the water extract were made with soil 8, and at one period with soil 1. The result of these tend to show that considerable fluctuations may take place from day to day. The results of these two studies are plotted in figures 22 to 24. It will be seen that the fluctuations in general occur simultaneously in both containers and so will not alter the relationship of the graphs for the planted and unplanted soils. They show, however, that small differences in the range of the graphs can not be considered sig-

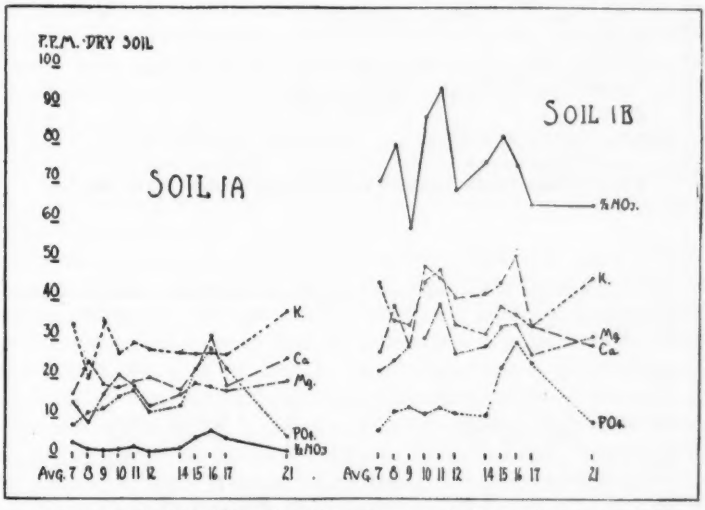

FIG. 22.—Graphs of the daily studies of the water extract of soils 1A and 1B, season of 1916.

nificant. The general range of the graphs is believed to represent an average figure, but small variations between soils should always be disregarded. This would also indicate that an expression of the differences in water-soluble material can only be given by a series of related observations.

DISCUSSION AND DEDUCTIONS

In the foregoing studies it is believed that the limitations as well as the possibilities of the experimental methods have been pointed out. It is earnestly desired that no deductions should be drawn which are not conservatively justified by the data presented.

It should be noted that the results have been obtained on 13 soils which comprise only two distinct soil types. These types are, however,

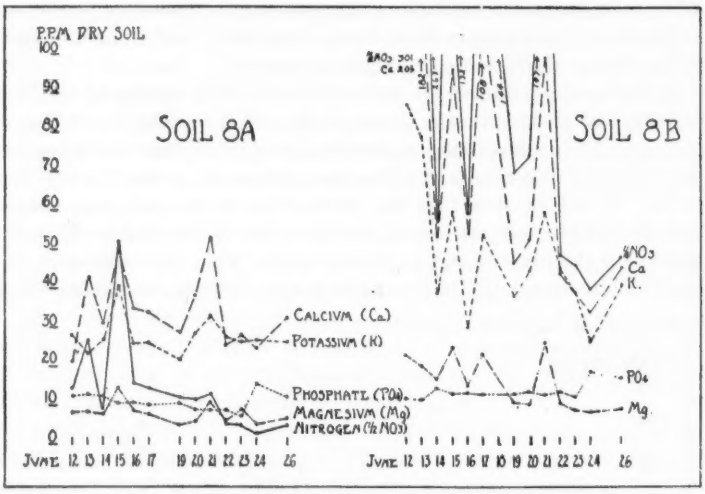

FIG. 23.—Graphs of the daily studies of the water extract of soils 8A and 8B, July, 1916.

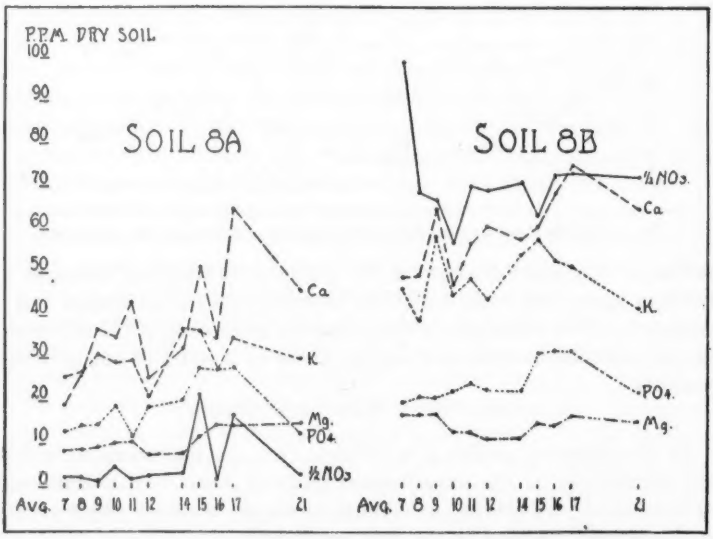

FIG. 24.—Graphs of the daily studies of the water extract of soils 8A and 8B, August, 1916.

very dissimilar in their nature; the silty clay loams are representative of decidedly complex soils with appreciable amounts of clay and other colloids, while the fine sandy loams belong to the light open soils which are common in the West. The extraction graphs yielded by both types are so similar that it is believed that comparisons can safely be made both within the types and between the two groups.

The extractions of the season of 1916 are those to which the greatest importance is attached and are those which will largely be considered in this discussion. The previous year's work brought the soils into comparable condition and also showed the probable limits of the agreement between duplicates. It is believed that the results obtained in this second season throw some light on several disputed points. The method of constant comparison between the cropped and uncropped soil is considered essential for the success of such a study. Only in this manner can any conception of the inherent capacity of a soil be obtained. When a large crop is growing on a soil, it is possible for it to affect the soluble nutrients so that the extract given by it will be equal to a moderately good or fairly poor soil.

Such a condition is seen with three fine sandy loams: No. 7, Hanford fine sandy loam, a soil of moderate production; No. 8, Fresno fine sandy loam, a very good soil; and No. 9, Kimball fine sandy loam, a soil which has produced poor crops.

The nutrients extracted from each of these three soils when cropped give practically duplicate graphs. But with the unplanted duplicate striking differences are seen. The better soils all show greater differences between the cropped and the uncropped soils than do the three poorest soils, No. 3, 9, 10, and 12. With these three it is possible that plant food is the limiting factor, but with certain soils of intermediate production, such as No. 4 and 10, it is less evident why these should not fall in the most productive group. It is claimed, however, that this method of study gives an expression of the inherent capacity of the soil to produce water-soluble plant food.

Between these three poor soils and the group of highest production there are large differences in the range of soluble nutrients. These three soils would not be classed as unfertile soils in general farming. The only one which had a small crop upon it when the original sample was collected was soil No. 12, Arnold fine sandy loam. The oats growing on this body of soil were noticeably smaller than in other portions of the field. Under the controlled conditions of the experiment the differences between these soils and the more productive must be considered significant, since they have been among the poorest soils each year. It may, therefore, be stated that among the 10 soils studied the 3 lowest in productivity also show the lowest inherent capacity to furnish soluble nutrients.

This conclusion is notably at variance with the earlier statements of Whitney and Cameron (*61*). It is believed that the experimental method which has been followed brings out the relationship between different soils with unusual clarity and effectiveness.

The influence of the crop on the soluble nutrients is another point which has been denied by the same authors. This is shown by the following quotation from Bureau of Soils, Bulletin 22:

> At the same time we have detected no constant decrease in the amount of soluble salts which could be easily detected with the methods used during the advance stages of growth of the crop, notwithstanding the considerable withdrawal there must be by the plants (*61, p. 60*).

The contrast between the curves of the planted and unplanted soils is evident at the most cursory glance. It is also clearly shown that the soil did not immediately recover and yield the same quantities of soluble nutrients as the uncropped plot, even after the crop was recovered. At the last observation recorded, on February 12, there was still an appreciable difference between the duplicate containers. In this connection it is pertinent to refer to the data obtained in a preliminary study in which a cropped soil was extracted with a diluted solution from an uncropped portion of it. In that study it was shown that this diluted solution exerted a depressing effect on the nutrients extracted from the cropped soil. This has an important application.

At the period of greatest growth of the crop, the water extract of the cropped soil approached much more closely to distilled water in the case of the planted soil than it did with the unplanted duplicate. In consequence of this fact, a greater portion of the extract obtained from it was from the solution of the actual soil minerals than was the case with the uncropped soil. The real difference between the two duplicate containers was therefore greater than the graphs would indicate. They can only be taken as the minimum difference which actually existed.

The data obtained by Hoagland, using the freezing-point method, corroborate this difference between the planted and unplanted soils. He has also observed that soils 9, Kimball fine sandy loam, and 12, Arnold fine sandy loam, are notably lower than any of the other soils in the concentration of their solutions. This coincided with the observations made from a study of the water extracts. Considering soil 3, Yolo silty clay loam, the next lowest soil in water extract, he could not draw any definite conclusion.

Jensen (*32*) in his studies on sugar beets has described a decrease in water-soluble nutrients and has also found this less noticeable in the case of phosphates. King's (*35*) figures also showed some decrease in soluble compounds as the crop advanced in growth. Harris and Butt (*24*) have observed differences in soluble salts and nitrates between cropped and fallow soils. It is believed, however, that the use of the unplanted duplicate soil and the periodic observations made upon it and the cropped

container have given a better expression of the potential power of the soil than has been obtained in the past.

The study of the unplanted soil is especially valuable because of the definite information which it furnishes in regard to the effect of fallowing and cultivation. From the results of the present investigation it can be stated that the changes occurring in water-soluble compounds, both organic and inorganic, as the result of these practices, are great and far-reaching in effect. They entirely justify the importance attached to such treatment in the past. In biennial cropping, alternating with fallowing, as practiced in California, it is probable that fully as much is gained from the increase of water-soluble nutrients as from the moisture stored up in the soil.

In the preceding studies the data obtained have been considered solely as a measure of the water-soluble nutrients obtained by a conventional procedure of extraction. From the work performed by Hoagland in collaboration the amounts extracted are definitely related to the actual soil solution. Even though the figures so obtained do indicate a range of concentrations higher than the actual truth, it has been previously pointed out that this does not alter the relationships which have been established. It is therefore believed, with this corroborative evidence, that the changes observed in the water extract reflect actual changes in the soil solution.

SUMMARY

(1) The water-soluble nutrients in 13 soils, of two different types, have been periodically determined during two seasons.

(2) Throughout the second season comparisons were made between the planted soil and its uncropped duplicate.

(3) Notable differences were observed between the nitrates, calcium, potassium, and magnesium present in the water extracts from the cropped and uncropped soils.

(4) The phosphates did not exhibit corresponding differences. Great dissimilarities were observed in the phosphate content of different soils, but in any one soil the amount was practically constant in both the cropped and uncropped plot.

(5) Striking differences occurred between the soluble nutrients present in the various uncropped soils.

(6) While the crops were growing, the concentrations of nutrients in 8 of the 13 planted soils were practically the same. These 8 included both good and poor soils.

(7) The three poorest soils yielded the smallest amounts of water-soluble nutrients and the smallest differences between the cropped and uncropped duplicates.

(8) The comparisons between the planted and unplanted duplicates furnished valuable indexes of the inherent capacities of the soils to produce nutrients.

(9) The accuracy of the methods of analysis and of the extraction procedure employed was determined, and the mean and maximum errors involved were estimated.

(10) The amounts of the water-soluble nutrients obtained by varying the ratio of soil to water were studied. The relationship of the compounds extracted did not change essentially in the lower concentrations.

(11) By comparison with freezing-point determinations the concentration of the soil solution calculated from the water extract was shown to be from two to four or five times as great as the actual soil solution.

(12) Variations in the water extract were correlated with variations in the freezing points of the same samples of soil.

(13) From the results of the freezing-point determinations it is concluded that variations in the water extract reflect actual changes in the soil solution.

(14) The results of the investigation show that large amounts of water-soluble nutrients are developed by cultivation, fallowing, and biennial cropping, and demonstrate the soundness of these practices.

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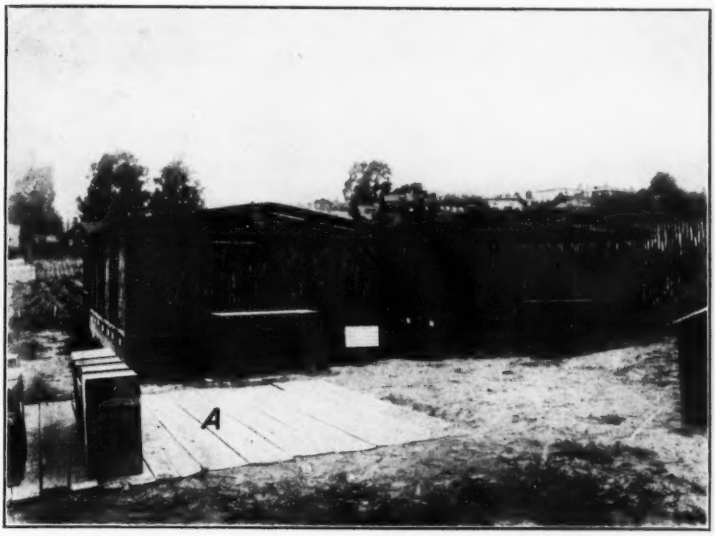
PLATE 14

A.—General views of soil containers.

B.—Bins for storage of surplus soil.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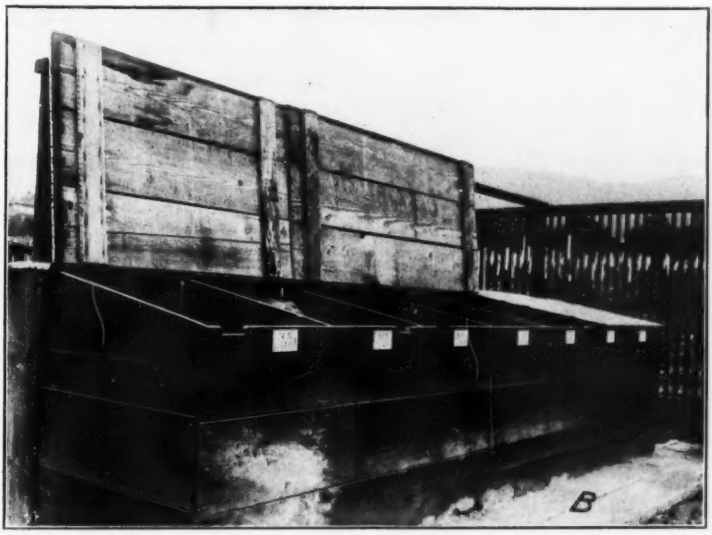
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THE FREEZING-POINT METHOD AS AN INDEX OF VARIATIONS IN THE SOIL SOLUTION DUE TO SEASON AND CROP GROWTH[1]

By D. R. HOAGLAND,

Assistant Professor of Agricultural Chemistry, College of Agriculture of the University of California

INTRODUCTION

In the preceding article by Stewart (*8*)[2] it has been conclusively shown that water extracts of different soils may have widely varying concentrations of important nutrient elements, and that the water-soluble substances in the 13 cropped soils were strikingly diminished in quantity when the barley crop had reached its maximum power of absorption. In the uncropped soils significant seasonal variations were also noted. These studies suggested the importance of correlating the water extracts with the actual soil solution, the immediate source of nutrients for the plant.

Various attempts have been made to separate the soil solution, but in no case has any appreciable quantity of solution been obtained when a soil contained only the optimum percentage of moisture. Recently Bouyoucos and McCool (*2*) have proposed a method which seems capable of giving direct experimental evidence concerning the concentration of the soil solution. The procedure consists in determining the depression of the freezing point in the soil itself under varying moisture conditions. The soils used in the investigation described by Stewart seemed uniquely adapted for further study by the freezing-point method. Accordingly such determinations were made on the various soils under controlled conditions, and the present paper deals with observations made on the depressions of the freezing point in soils as affected by season, cropping, moisture content, and other factors of significance in plant growth.

GENERAL METHOD OF PROCEDURE

The technic employed was essentially that described by Bouyoucos and McCool (*2*). The experience of the Agricultural Chemistry Laboratory confirms their statements with regard to the possibility of obtaining closely agreeing duplicates and general consistency of results. The freezing-point blank with distilled water, however, was not found to maintain a constant value from day to day, and to obviate any possible

[1] Approved for publication in the Journal of Agricultural Research by the Director of the Agricultural Experiment Station of the University of California.

[2] Reference is made by number (italic) to "Literature cited," p. 394-395.

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error from this source, determinations on pure water were checked several times each day. The general magnitude of error in technic is indicated by the following typical instances of duplicate experiments:

Soil No.	Freezing-point depression.	Soil No.	Freezing-point depression.
	°C.		°C.
10A	0.065	15A	0.052
10A	.062	14A	.043
1B	.066	14A	.050
1B	.069	4B	.157
15A	.049	4B	.155

DESCRIPTION OF SOILS USED

In the article by Stewart (*8*) the reader will find a detailed description of the soils under the same laboratory numbers. For the sake of convenient reference, a list of the soils used is included here (Table I). Each soil was investigated under three general conditions: (1) Soil from tanks in which barley crop was grown for two seasons; (2) corresponding soils kept under identical conditions but with no crop the second season; (3) soils air-dried, sifted, and kept two years in closed bins. All tank soils were kept constantly at nearly optimum moisture contents with distilled water.

TABLE I.—*Description of soils used in this investigation*

Laboratory No.	Soil series and type.	Origin.
1, 2, 3	Yolo silty clay loam	Sacramento Valley.
4, 5, 6	do	Santa Clara Valley.
7	Hanford fine sandy loam	Southern California.
8	Fresno fine sandy loam	San Joaquin Valley.
9	Kimball fine sandy loam	Southern California.
10	Tejunga fine sandy loam	Do.
11	Madera fine sandy loam	San Joaquin Valley.
12	Arnold fine sandy loam	Do.
14	Standish fine sandy loam	Virgin desert soil.

UNFREE WATER OF SOILS

One of the most important factors affecting the concentration of the soil solution is the moisture content. This has already been pointed out by Bouyoucos and McCool, and the former has recently devised a dilatometer method for more accurately measuring the unfree water of a soil (*1*). In the present investigation an attempt was made to approximate the unfree water in each soil by careful determinations of the freezing-point depressions at different moisture contents. These data could then be used in reducing the observed depressions to definite and comparable moisture percentages, especially where the observed

moisture contents differed only slightly from the standard. It has been shown by Bouyoucos and McCool that freezing-point depressions vary with the water content of the soil, not usually in direct ratio, but in such manner as to necessitate the assumption that a certain fraction of the total water present is so combined that it does not form an effective part of the soil solution and is not subject to freezing. The percentage of combined water would vary greatly with the type of soil, clay soils having a large proportion of their water in the unfree state. The above considerations, advanced by Bouyoucos and McCool, have been made the basis for the determinations of unfree water in the soils used in this investigation. Portions of each soil were divided into two samples the moisture contents of which were so adjusted as to give a difference of about 5 per cent. Each sample was thoroughly mixed and kept overnight in a tight jar. Careful determinations of total moisture and freezing-point depression were then made. From these data it is possible to calculate what proportion of the moisture must be subtracted from the total in order that the percentages of free water may give the same ratios as the freezing-point depressions. Such estimates may not have a high degree of accuracy, but it is probably sufficient for the purposes in hand. Table II presents the results for the unfree water in each soil.

TABLE II.—*Estimation of unfree water in soils*

Soil No.	Moisture.	Freezing-point depression.	Unfree water.	Soil No.	Moisture.	Freezing-point depression.	Unfree water.
	Per cent.	*° C.*	*Per cent.*		*Per cent.*	*° C.*	*Per cent.*
1C	20.0	0.098	18.0	8C	16.6	0.215	4.0
1C	22.4	.034		8C	8.1	.655	
2C	18.0	.140	13.0	9C	12.8	.099	6.0
2C	23.0	.069		9C	17.2	.059	
3C	18.4	.357	14.0	10C	12.8	.153	8.0
3C	24.0	.149		10C	17.8	.074	
4C	19.6	.362	13.0	11C	13.2	.331	6.0
4C	23.6	.210		11C	18.8	.197	
5C	18.8	.089	13.0	12C	13.2	.130	4.0
5C	23.2	.050		12C	18.0	.089	
6C	19.6	.282	17.7	14C	14.0	.254	7.5
6C	24.4	.079		14C	18.4	.149	
7C	12.4	.284	6.0				
7C	17.6	.167					

SEASONAL VARIATIONS IN CROPPED AND IN UNCROPPED SOILS

One of the primary objects of this investigation was to follow through the season the concentrations of the soil solution in each soil and to compare at each period of sampling the cropped soils with their uncropped duplicates. The first determinations of freezing-point depressions were made early in July, 1916, and at intervals from that date until the following May. The barley crop was planted in May, 1916, and harvested

in August. The samples of soil used in this work were identical with those employed by Stewart in making water extractions. In general, the moisture contents of the uncropped and cropped soils were very similar, but it was not always feasible to keep them in absolute agreement. The data are therefore presented in two forms: First, as a table showing the observed depressions and actual percentages of total moisture present, together with the corresponding osmotic pressures and parts per million of total solids in solution, as calculated by the methods of

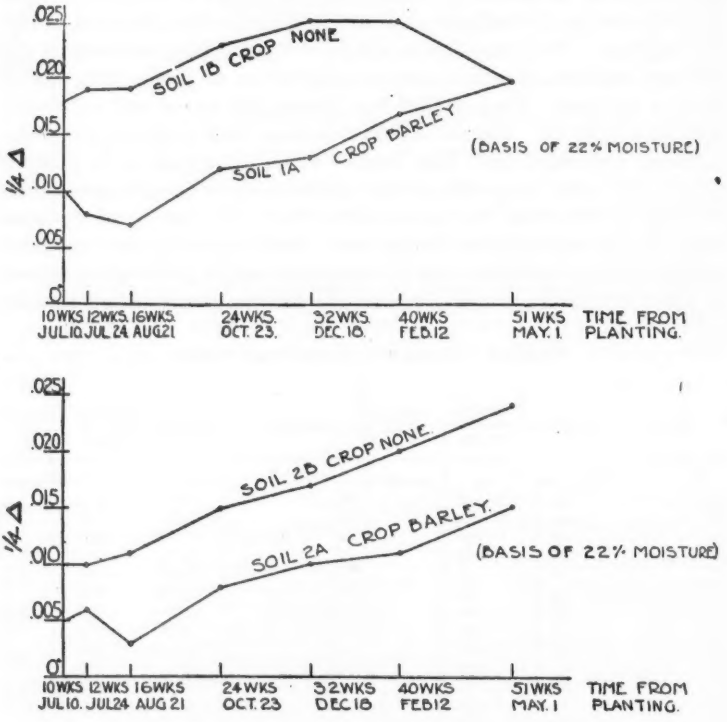

FIG. 1.—Graphs of the depressions of the freezing point in soils 1 and 2, with and without crop.

Bouyoucos and McCool. In the second place, the observed depressions have been calculated to uniform moisture contents, 17 per cent for all of the fine sandy loams and 22 per cent for the silty clay loams. In making these estimates the percentages of unfree water already presented have been used. The corrected depressions have been plotted for each pair of soils. In this way the cropped and the uncropped soils, as well as the different soils in each group, may be compared readily (fig. 1–8). (Cf. Table III.)

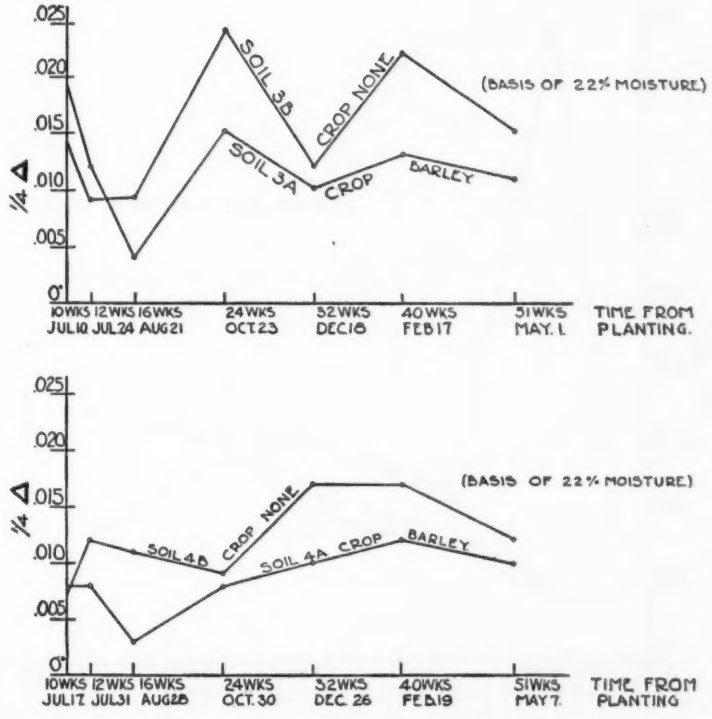

FIG. 2.—Graphs of the depressions of the freezing point in soils 3 and 4, with and without crop.

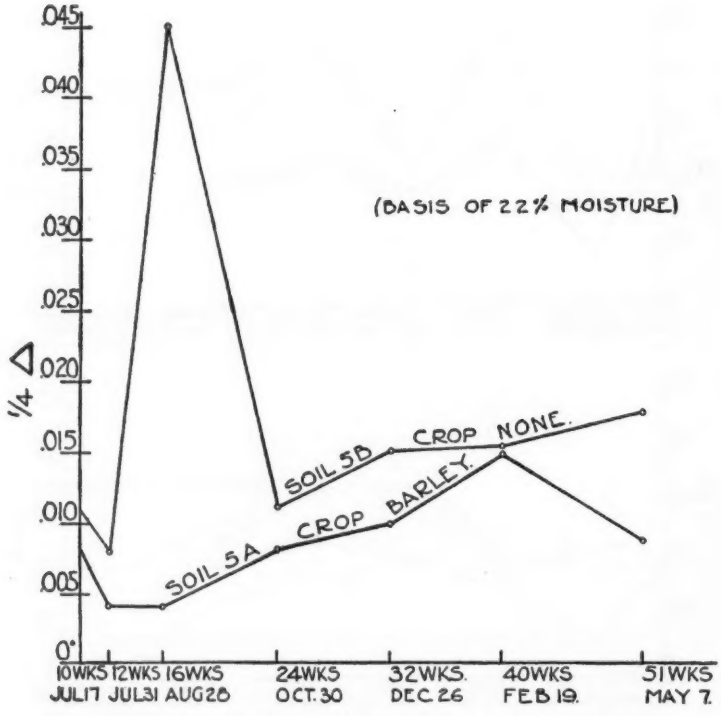

FIG. 3.—Graphs of the depressions of the freezing point in soil 5, with and without crop.

FIG. 4.—Graphs of the depressions of the freezing point in soil 6, with and without crop.

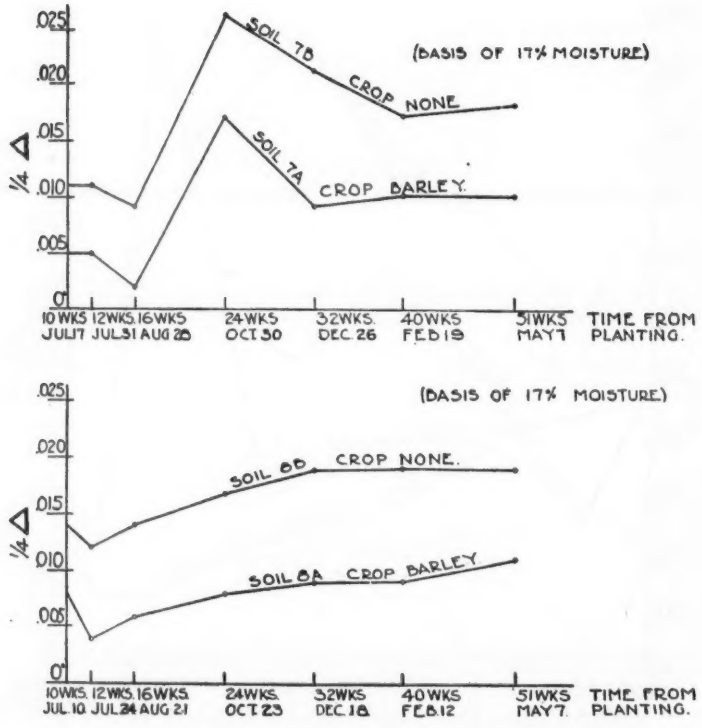

FIG. 5.—Graphs of the depressions of the freezing point in soils 7 and 8, with and without crop.

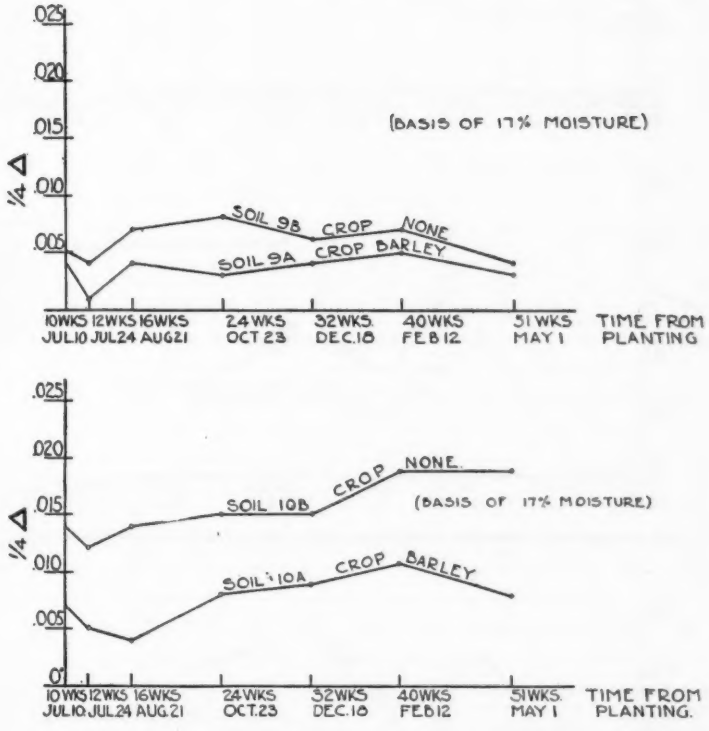

FIG. 6.—Graphs of the depressions of the freezing point in soils 9 and 10, with and without crop.

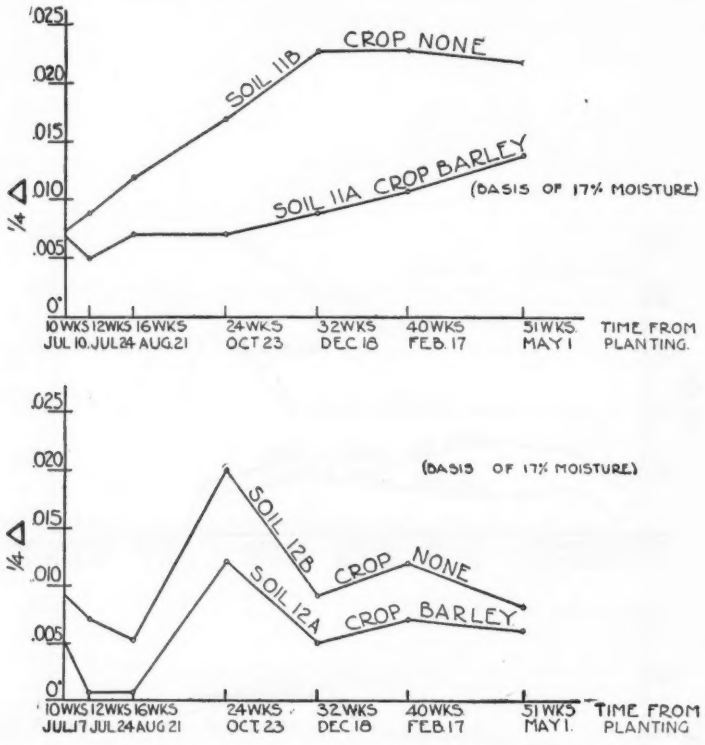

FIG. 7.—Graphs of the depressions of the freezing point in soils 11 and 12, with and without crop.

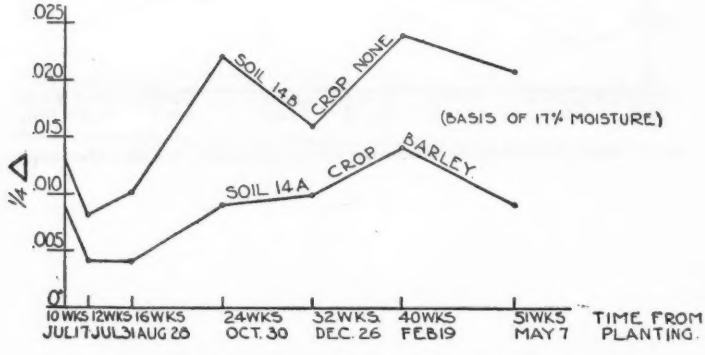

FIG. 8.—Graphs of the depressions of the freezing point in soil 14, with and without crop.

TABLE III.—*Observed and calculated freezing-point depressions*

Date.	Moisture.		Observed freezing-point depression.		Osmotic pressure (atmospheres).		Calculated total solids in soil solution.		Freezing-point depression calculated to uniform moisture.[a]	
	Soil 1A.	Soil 1B.	Soil 1A.	Soil 1B.	Soil 1A.	Soil 1B.	Soil 1A.	Soil 1B.	Soil 1A.	Soil 1B.
	P. ct.	*P. ct.*	° *C.*	° *C.*			*P. p. m.*	*P. p. m.*	° *C.*	° *C.*
July 10	23. 2	22. 4	0. 030	0. 064	0. 36	0. 77	900	2, 000	0. 039	0. 070
July 24	22. 5	22. 7	. 029	. 065	. 35	. 78	900	2, 000	. 033	. 076
Aug. 21	23. 9	23. 0	. 019	. 062	. 23	. 74	600	1, 900	. 028	. 77
Oct. 23	21. 8	21. 1	. 050	. 118	. 60	1. 43	1, 600	3, 700	. 047	. 091
Dec. 18	23. 4	22. 3	. 037	. 095	. 44	1. 15	1, 200	3, 000	. 050	. 102
Feb. 12	22. 7	21. 7	. 056	. 108	. 68	1. 31	1, 800	3, 400	. 066	. 100
May 1	21. 9	20. 3	. 082	. 138	. 99	1. 56	2, 600	4, 300	. 080	. 079
	Soil 2A.	Soil 2B.	Soil 2A.	Soil 2B.	Soil 2A.	Soil 2B.	Soil 2A.	Soil 2B.	Soil 2A.	Soil 2B.
July 10	20. 4	21. 4	0. 026	0. 044	0. 32	0. 53	800	1, 400	0. 021	0. 041
July 24	19. 7	20. 8	. 034	. 047	. 41	. 56	1, 100	1, 500	. 025	. 041
Aug. 21	23. 7	21. 3	. 008	. 049	. 10	. 59	300	1, 500	. 010	. 045
Oct. 23	18. 3	18. 9	. 055	. 092	. 66	1. 11	1, 700	2, 900	. 032	. 060
Dec. 18	20. 4	20. 0	. 047	. 087	. 56	1. 05	1, 500	2, 700	. 039	. 068
Feb. 12	20. 2	20. 2	. 056	. 101	. 68	1. 22	1, 800	3, 200	. 045	. 081
May 1	17. 4	17. 3	. 131	. 201	1. 47	2. 42	4, 100	6, 300	. 064	. 096
	Soil 3A.	Soil 3B.	Soil 3A.	Soil 3B.	Soil 3A.	Soil 3B.	Soil 3A.	Soil 3B.	Soil 3A.	Soil 3B.
July 10	18. 6	22. 2	0. 130	0. 055	1. 46	0. 66	4, 100	1, 700	0. 075	0. 056
July 24	19. 0	22. 2	. 078	. 036	. 94	. 44	2, 400	1, 100	. 049	. 037
Aug. 21	22. 0	22. 7	. 017	. 034	. 20	. 41	500	1, 100	. 017	. 037
Oct. 23	20. 5	20. 9	. 075	. 110	. 90	1. 33	2, 300	3, 400	. 061	. 095
Dec. 18	20. 9	20. 7	. 048	. 060	. 58	. 72	1, 500	1, 900	. 041	. 050
Feb. 12	20. 6	19. 9	. 062	. 120	. 74	1. 45	1, 900	3, 800	. 051	. 089
May 1	19. 1	17. 5	. 068	. 135	. 82	1. 52	2, 100	4, 200	. 043	. 059
	Soil 4A.	Soil 4B.	Soil 4A.	Soil 4B.	Soil 4A.	Soil 4B.	Soil 4A.	Soil 4B.	Soil 4A.	Soil 4B.
July 17	18. 8	18. 5	0. 048	0. 047	0. 58	0. 56	1, 500	1, 500	0. 031	0. 029
July 31	18. 6	19. 6	. 050	. 066	. 60	. 80	1, 600	2, 100	. 031	. 048
Aug. 28	19. 2	20. 0	. 017	. 057	. 20	. 68	500	1, 800	. 012	. 044
Oct. 30	17. 3	16. 7	. 068	. 082	. 82	. 99	2, 100	2, 600	. 033	. 034
Dec. 26	19. 3	18. 0	. 055	. 121	. 66	1. 46	1, 700	3, 800	. 038	. 067
Feb. 19	17. 6	17. 2	. 098	. 148	1. 19	1. 179	3, 100	4, 600	. 050	. 069
May 7	16. 5	15. 8	. 106	. 157	1. 29	1. 89	3, 300	4, 900	. 041	. 049

[a] Soils 1, 2, 3, 4, 5, and 6 calculated to 22 per cent of moisture. Soils 7, 8, 9, 10, 11, 12, and 14 calculated to 17 per cent of moisture.

TABLE III.—*Observed and calculated freezing-point depressions*—Continued

Date.	Moisture.		Observed freezing-point depression.		Osmotic pressure (atmospheres).		Calculated total solids in soil solution.		Freezing-point depression calculated to uniform moisture.	
	Soil 5A.	Soil 5B.	Soil 5A.	Soil 5B.	Soil 5A.	Soil 5B.	Soil 5A.	Soil 5B.	Soil 5A.	Soil 5B.
	P. ct.	*P. ct.*	*° C.*	*° C.*			*P. p. m.*	*P. p. m.*	*° C.*	*° C.*
July 17	16. 2	18. 7	0. 093	0. 069	1. 13	0. 83	2, 900	2, 200	0. 033	0. 044
July 31	18. 4	20. 6	. 029	. 039	. 35	. 47	900	1, 200	. 017	. 033
Aug. 28	21. 9	21. 1	. 017	. 157	. 20	1. 89	500	4, 900	. 017	. 141
Oct. 30	16. 8	17. 5	. 079	. 088	. 95	1. 07	2, 500	2, 800	. 033	. 044
Dec. 26	18. 2	18. 0	. 066	. 106	. 80	1. 29	2, 100	3, 300	. 038	. 059
Feb. 19	18. 1	17. 2	. 106	. 115	1. 29	1. 39	3, 300	3, 600	. 060	. 054
May 7	16. 9	19. 2	. 079	. 101	. 95	1. 22	2, 500	3, 200	. 034	. 070
	Soil 6A.	Soil 6B.	Soil 6A.	Soil 6B.	Soil 6A.	Soil 6B.	Soil 6A.	Soil 6B.	Soil 6A.	Soil 6B.
July 17	18. 8	23. 8	0. 399	0. 097	4. 81	1. 17	12, 000	3, 000	0. 102	0. 138
July 31	.....	25. 2	.....	. 086	.....	1. 05	.....	2, 700	.....	. 150
Aug. 28	23. 4	24. 9	. 040	. 072	. 48	. 86	1, 300	2, 300	. 053	. 121
Oct. 30	24. 1	24. 4	. 068	. 101	. 82	1. 22	2, 100	3, 200	. 101	. 157
Dec. 26	24. 5	24. 8	. 085	. 103	1. 02	1. 25	2, 700	3, 200	. 135	. 170
Feb. 19	24. 8	25. 0	. 066	. 126	. 80	1. 52	2, 100	3, 900	. 109	. 214
May 7	23. 0	22. 6	. 104	. 153	1. 26	1. 85	3, 300	4, 800	. 128	. 174
	Soil 7A.	Soil 7B.	Soil 7A.	Soil 7B.	Soil 7A.	Soil 7B.	Soil 7A.	Soil 7B.	Soil 7A.	Soil 7B.
July 17	13. 7	15. 9	0. 028	0. 048	0. 34	0. 58	900	1, 500	0. 020	0. 043
July 31	13. 6	16. 9	. 026	. 042	. 32	. 50	800	1, 300	. 018	. 042
Aug. 28	19. 3	16. 6	. 007	. 035	. 08	. 42	200	1, 100	. 009	. 034
Oct. 30	14. 9	13. 6	. 082	. 151	. 99	1. 82	2, 600	4, 700	. 066	. 104
Dec. 26	15. 9	14. 7	. 038	. 108	. 46	1. 31	1, 200	3, 400	. 034	. 085
Feb. 19	14. 6	14. 0	. 053	. 093	. 64	1. 13	1, 700	2, 900	. 041	. 068
May 7	12. 5	12. 8	. 070	. 116	. 84	1. 41	2, 200	3, 600	. 041	. 072
	Soil 8A.	Soil 8B.	Soil 8A.	Soil 8B.	Soil 8A.	Soil 8B.	Soil 8A.	Soil 8B.	Soil 8A.	Soil 8B.
July 10	13. 2	14. 4	0. 038	0. 064	0. 46	0. 77	1, 200	2, 000	0. 027	0. 051
July 24	14. 1	14. 8	. 015	. 053	. 18	. 64	500	1, 700	. 012	. 044
Aug. 21	15. 9	15. 9	. 021	. 056	. 25	. 68	700	1, 800	. 019	. 051
Oct. 23	9. 9	10. 0	. 060	. 138	. 72	1. 56	1, 900	4, 300	. 027	. 064
Dec. 18	12. 7	12. 5	. 049	. 111	. 59	1. 34	1, 500	3, 400	. 033	. 073
Feb. 12	10. 6	10. 8	. 062	. 135	. 74	1. 52	1, 900	4, 200	. 032	. 071
May 7	8. 2	7. 9	. 122	. 214	1. 47	2. 58	3, 800	6, 700	. 039	. 071
	Soil 9A.	Soil 9B.	Soil 9A.	Soil 9B.	Soil 9A.	Soil 9B.	Soil 9A.	Soil 9B.	Soil 9A.	Soil 9B.
July 10	14. 3	13. 4	0. 018	0. 034	0. 22	0. 41	600	1, 100	0. 014	0. 023
July 24	14. 0	13. 2	. 007	. 026	. 08	. 32	200	800	. 005	. 017
Aug. 21	16. 9	13. 1	. 014	. 042	. 17	. 50	400	1, 300	. 014	. 027
Oct. 23	10. 7	9. 7	. 028	. 092	. 34	1. 11	900	2, 900	. 012	. 031
Dec. 18	11. 0	10. 6	. 031	. 058	. 37	. 70	1, 000	1, 800	. 014	. 024
Feb. 12	9. 4	9. 5	. 057	. 087	. 68	1. 05	1, 800	2, 700	. 018	. 028
May 1	7. 1	6. 9	. 118	. 200	1. 43	2. 41	3, 700	6, 300	. 012	. 016

TABLE III.—*Observed and calculated freezing-point depressions*—Continued

Date.	Moisture.		Observed freezing-point depression.		Osmotic pressure (atmospheres).		Calculated total solids in soil solution.		Freezing-point depression calculated to uniform moisture.	
	Soil 10A.	Soil 10B.	Soil 10A.	Soil 10B.	Soil 10A.	Soil 10B.	Soil 10A.	Soil 10B.	Soil 10A.	Soil 10B.
	P. ct.	*P. ct.*	*° C.*	*° C.*			*P. p. m.*	*P. p. m.*	*° C.*	*° C.*
July 10	15.7	16.6	0.037	0.056	0.44	0.67	1,200	1,800	0.028	0.054
July 24	16.0	16.1	.023	.051	.28	.61	700	1,600	.021	.047
Aug. 21	19.6	17.0	.012	.057	.14	.68	400	1,800	.015	.057
Oct. 23	14.9	13.6	.041	.099	.49	1.19	1,300	3,100	.033	.061
Dec. 18	15.1	14.6	.046	.079	.55	.95	1,400	2,500	.036	.058
Feb. 12	14.1	13.4	.066	.125	.79	1.51	2,100	3,900	.045	.075
May 1	11.5	11.0	.094	.228	1.14	2.75	2,900	7,100	.033	.076
	Soil 11A.	Soil 11B.	Soil 11A.	Soil 11B.	Soil 11A.	Soil 11B.	Soil 11A.	Soil 11B.	Soil 11A.	Soil 11B.
July 10	14.9	11.2	0.034	0.060	0.41	0.72	1,100	1,900	0.028	0.028
July 24	12.7	15.8	.035	.041	.42	.49	1,100	1,300	.021	.037
Aug. 21	16.6	16.3	.027	.052	.32	.62	800	1,600	.026	.049
Oct. 23	13.9	13.2	.037	.101	.44	1.22	1,200	3,200	.027	.066
Dec. 18	14.5	13.6	.047	.134	.56	1.51	1,500	4,200	.036	.093
Feb. 17	13.3	13.5	.065	.133	.78	1.50	2,000	4,200	.043	.091
May 1	11.0	10.7	.121	.203	1.47	2.45	3,800	6,300	.055	.087
	Soil 12A.	Soil 12B.	Soil 12A.	Soil 12B.	Soil 12A.	Soil 12B.	Soil 12A.	Soil 12B.	Soil 12A.	Soil 12B.
July 17	11.1	12.3	0.033	0.054	0.40	0.65	1,000	1,700	0.018	0.034
July 24	14.4	13.5	.001	.036	.01	.44	50	1,100	.001	.026
Aug. 21	16.3	14.5	.003	.026	.04	.32	100	800	.003	.021
Oct. 23	14.4	11.4	.061	.138	.73	1.56	1,900	4,300	.049	.079
Dec. 18	13.9	11.7	.030	.059	.36	.71	900	1,800	.023	.035
Feb. 17	12.7	11.4	.043	.083	.52	1.01	1,300	2,600	.029	.047
May 1	10.0	9.6	.048	.077	.58	.92	1,500	2,400	.022	.033
	Soil 14A.	Soil 14B.	Soil 14A.	Soil 14B.	Soil 14A.	Soil 14B.	Soil 14A.	Soil 14B.	Soil 14A.	Soil 14B.
July 17	15.7	18.4	0.041	0.045	0.49	0.54	1,300	1,400	0.035	0.052
July 31	17.9	19.1	.013	.027	.16	.32	400	800	.014	.033
Aug. 28	20.4	19.1	.010	.031	.12	.37	300	1,000	.014	.038
Oct. 30	17.5	16.2	.033	.095	.40	1.15	1,000	3,000	.035	.087
Dec. 26	17.0	16.5	.039	.068	.47	.82	1,200	2,100	.039	.065
Feb. 19	16.1	15.0	.063	.123	.76	1.49	2,000	3,800	.057	.097
May 7	15.7	20.5	.043	.060	.52	.72	1,300	1,900	.037	.082

It is strikingly evident from these data (Table III) that the freezing-point depressions are not constant during the season, and that the concentrations of the soil solution are uniformly lower in the cropped soils than in the same soils uncropped. This latter observation is especially noteworthy, since comparisons of two samples of the same soil are peculiarly applicable. Any errors due to unfree water, type of soil, optimum moisture content, etc., would be practically constant. The same general relations hold, whether the original data are considered, or the corrected figures as used in the graphs. The only difference is that more exact comparisons may be made when the moisture contents are reduced to a uniform percentage.

The logical conclusion from the results given in Table III is that the concentration of the soil solution may vary widely at different periods of the year, and that the growth of the plant has a pronounced effect in lowering the concentration. Furthermore, this effect is of long duration. The soils which had been cropped are still decidedly lower in the concentration of the soil solution, as compared with the fallowed soils, eight months after harvesting the crop. It does not necessarily follow that the differences between the cropped and the uncropped soils are to be ascribed solely to the depletion of the soil solution by the plant. The evidence presented by Burd (*3*) is confirmatory of the idea that certain biological activities are more intense in the soil without crop, as shown by the increased production of nitrates and greater solubility of calcium and magnesium. It is nevertheless true that the lowest concentrations in the cropped soils occur at about the time when the crop has completed its maximum absorption of nutrients. In certain of the fine sandy loams the concentrations have been reduced to a very low point, corresponding to only a few hundred parts per million of total solids. This condition must be the result of withdrawals by the plant. The magnitudes of absorption, as given by Burd, are quite comparable with quantities present in the soil solution. After the minimum has been reached at the height of the growing season, the freezing-point depressions slowly increase up to the last date recorded in the graphs, May 1. It is highly probable that several weeks after cultivation a more marked increase in the concentration of the soil solution would take place.

At this point it is desirable to compare the data presented by Stewart (*8*) for the water extracts with the determinations made by the freezing-point method. It will be noted that the same general relations obtain in both cases. All the elements for which analysis was made are subject to marked fluctuations, with the exception of phosphorus. This subject will be given further consideration later in the article.

VARIOUS FACTORS AFFECTING THE SOIL SOLUTIONS

As a result of the observations on the tank soils which have just been described, it was decided to study various other factors possibly affecting the depression of the freezing point. What conditions other than cropping might increase or decrease concentration? The first step was to study the soils which had been held in a nearly air-dry state in bins. The results of these determinations have already been set forth in Table II, and comparisons may now be made between tank soils and the corresponding bin soils. It will at once be noted that a number of the latter show very much higher concentrations of the soil solution than either the cropped or the uncropped soils during most of the season. All three portions of each soil were originally derived from the same sifted and homogenous mass of soil. The existing differences must therefore be due to subsequent treatments which are correlated with three levels of concentration: (1) A very low concentration in the cropped soil, (2) a higher one in the uncropped soil, and (3) highest of all in some of the stored soils. The latter in a number of cases gave four or five times as great a depression of the freezing point as the corresponding cropped soils. The fact that the uncropped soils in the tanks had in some cases a less concentration of the soil solution than the stored soils may be explained by the treatment of the preceding year when both tank soils were cropped. It may also be true that long storage of the bin soils under the special conditions has brought about a decomposition of soil minerals as well as an increase in nitrates, with the result that a more highly concentrated soil solution is produced as soon as the soil is mixed with its optimum quantity of water. The extractions of the bin soils confirmed the freezing-point results. Water extracts showed a correspondingly high solubility for nearly all constituents.

With the establishment of the relations of freezing-point lowerings of soils under several conditions it became of interest to make a somewhat more detailed study in an effort to determine what factors are especially active in changing the concentration of the soil solution.

EFFECT OF INCUBATION ON CONCENTRATION OF SOIL SOLUTION

The first experiments dealt with the effect of long standing at laboratory temperatures. Samples were obtained from the tank soils, and after the determinations of freezing-point lowerings portions were kept in tight Mason jars for from one to three months. At the end of the specified periods the freezing points were again determined, with the results given in Table IV.

TABLE IV.—*Effect of incubation at laboratory temperature on depressions of freezing point*

Soil No.	Moisture.	Freezing-point depression.		Soil No.	Moisture.	Freezing-point depression.		Soil No.	Moisture.	Freezing-point depression.	
		Dec. 27	Mar. 29			Dec. 19	Jan. 9–16			Oct. 23	Nov. 3
	Per cent	°C.	°C.		*Per cent*	°C.	°C.		*Per cent*	°C.	°C.
4A....	19.3	0.055	0.073	1A...	23.4	0.037	0.050	10B..	13.6	0.099	0.439
4B....	18.0	.121	.133	1B...	22.3	.095	.152				
5A....	18.2	.066	.127	2A...	20.4	.047	.050				
5B....	18.0	.106	.153	2B...	20.0	.087	.100			Dec. 5	Dec. 13
6A....	24.5	.085	.120	3A...	20.9	.048	.063				
6B....	24.8	.103	.149	3B...	20.7	.060	.110				
7A....	15.9	.038	.052	8A...	12.7	.049	.062	10B..	12.8	0.153	0.180
7B....	14.7	.108	.081	8B...	12.5	.111	.142	10B..	14.4	.127	.169
12A...	13.9	.030	.013	9A...	11.0	.031	.038	10B..	14.6	.120	.148
12B...	11.7	.059	.046	9B...	10.6	.058	.072	10B..	16.0	.092	.114
14A...	17.0	.039	.091	10A..	15.1	.046	.058	10B..	17.0	.080	.104
14B...	16.5	.068	.096	10B..	14.6	.079	.105	10B..	17.8	.074	.097

It will be evident from Table IV that in the majority of cases there has been a distinct increase in the depression of the freezing point under the conditions of storage. It is significant that at the end of the storage period the uncropped soils still maintain their superiority with regard to the concentration of the soil solution. The time at which the sample is taken may in some cases influence the further changes taking place at laboratory temperatures. This suggestion is supported by the data for soil 10B. The samples taken in November gave a much greater increase in concentration after standing than was the case with the sample taken in December. Doubtless these differences may be associated with conditions favorable for nitrate production, but the extraction experiments have shown that other elements are increased in solubility simultaneously with the increased production of nitrates.

EFFECT OF CARBON-DIOXID GAS ON CONCENTRATION OF SOIL SOLUTION

The increase in concentration of the soil solution noted above, as well as the seasonal changes, may probably be related to the activities of microorganisms and their production of carbon dioxid. Several experiments were therefore undertaken to demonstrate the effect of carbon dioxid gas on freezing-point depressions. A sample of soil 5A containing 17.7 per cent of water was placed in a stoppered bottle, and a current of carbon-dioxid gas was passed through the moist soil for about five minutes. This treatment was repeated several times. The bottle was then closed tightly and the soil permitted to stand overnight in contact with the atmosphere of carbon dioxid, after which the depression of the freezing point was determined and compared with another sample of the soil exactly the same but not treated with carbon dioxid. The control sample gave a depression of 0.083° C. and the treated soil 0.138°.

A similar experiment was performed on the 5B soil, containing 16.7 per cent of moisture. The results in this case were 0.156° depression for the control and 0.218° for the sample treated with carbon dioxid. It is evident from these data that the gas has a striking effect in increasing the concentration of the soil solution. Here, again, it is interesting to observe that the cropped and uncropped soils maintain the same general relation to each other, even after the treatment described. Water extractions made on the same soils showed that the total water-soluble material was considerably increased by the carbon-dioxid treatment. Calcium was particularly affected, but several other elements were also made more soluble.

EFFECT OF DRYING ON CONCENTRATION OF SOIL SOLUTION

One of the important influences which may affect the chemical state of the soil is that of drying. King (*4*) has shown that drying soils in the oven causes a considerable increase in the quantity of water-soluble material. Bouyoucos and McCool (*2*) have pointed out that the evidence obtained by their freezing-point method tends to the same conclusion. The writers have desired in the present research to apply this method to the study of the influence of air-drying on the soils from the tanks. Freezing-point depressions were first determined upon the moist soils, and samples were then spread out in the laboratory and allowed to become thoroughly air-dried. They were then mixed in a mortar with suitable quantities of distilled water, allowed to remain in closed jars for several hours, and the freezing points, as well as the percentages of moisture again determined. The results are given in Table V.

TABLE V.—*Effect of drying on freezing-point depressions*

Soil No.	Moisture.	Freezing-point depressions.	
		Original soil.	After drying and remoistening.[a]
	Per cent.	°C.	°C.
1A	22.7	0.056	0.050
1B	20.1	.108	.191
4A	17.6	.098	.089
4B	17.2	.148	.114
5A	17.7	.083	.068
5B	16.7	.156	.100
8A	10.6	.062	.058
8B	10.8	.135	.142
9A	9.4	.057	.083
9B	9.5	.087	.126
10A	14.1	.066	.094
10B	13.4	.125	.136
11A	13.3	.065	.067
11B	13.5	.133	.110

[a] Calculated to same moisture content as original sample.

It will be noted that there are no marked or consistent changes in the freezing-point depressions as a result of the air-drying. In samples 5A and 5B water extractions (1 to 5) were made with the result that only negligible increases occurred in the quantity of any of the constituents, with the exception of the organic matter which was made somewhat more soluble. It may be suggested that a further increase in the concentration of the soil solution might subsequently be caused through stimulation of bacterial activity caused by the additional organic nutriment made available. In this case the solubility of various elements would be increased indirectly by drying, but there is no evidence that nutrient elements become more soluble by the simple process of drying at ordinary temperatures.

EXPERIMENTS WITH LEACHED SOILS

All of the foregoing work has consistently indicated that a given soil may yield very different soil solutions under different conditions. In order to establish the lower limits, it was decided to leach several soils with distilled water and then determine the depression of the freezing point. These were determined immediately after leaching and at intervals over several months, during which time the soils were kept at laboratory temperature in closed jars. Table VI shows the results obtained.

TABLE VI.—*Effect of leaching on freezing-point depressions*

Soil No.	Treatment.	Freezing-point depression.				
		Before leaching.		After leaching.		
		Determined.	Water.	Date.	Determined.	Water.
		°C.	*Per cent.*		°C.	*Per cent.*
2B	800 gm. leached with 2 liters of water.	0.117	21.0	Nov. 3	0.034	
				Nov. 8	.021	
				Dec. 5	.033	20.4
				Feb. 26	.034	
				May 2	.030	
10B	do	.306	17.2	Nov. 3	.027	
				Nov. 8	.020	
				Dec. 5	.032	17.2
				Feb. 26	.040	
				May 2	.051	
8C	1,000 gm. leached with 10 liters of water.	.207	14.3	Jan. 9	.004	
				Feb. 6	.006	
				Feb. 26	.012	17.6
				May 2	.043	
5C	do	.060	21.5	Feb. 6	.013	
				Feb. 26	.049	22.4
				May 2	.064	

It seems quite clear from an inspection of these data that the concentration of the soil solution may be reduced to an extremely low point through leaching and that this condition is maintained over a considerable period of time. Leaching has been shown by Lipman (5) to inhibit bacterial action markedly, and in the absence of such activity, it seems that the ability of the soil to recover its high level of concentration is very limited.

RELATION OF WATER EXTRACTS TO SOIL SOLUTION

Before entering upon the final discussion it is desirable to consider at this point certain more detailed relations of water extracts to the soil solutions, as indicated by the freezing-point method. The work of Bouyoucos and McCool enables us to obtain very useful and interesting estimates of the concentration of the soil solution, but obviously it is only the total concentration which is measured. We are quite unable to predict the nature of the substances whose resultant effect is expressed by the lowering of the freezing point. Only by some method of water extraction is it possible to gain any insight into the proportions of individual elements. Various comparisons between osmotic pressures in the soil solution and concentrations in water extracts may, however, be made, which, in certain directions, make possible very interesting deductions.

When different soils are to be compared, the first inquiry must be concerned with the amount of lowering of the freezing point which occurs for each 100 p. p. m. of total solids. This phase of the question has already been investigated by Bouyoucos and McCool, who found that extracts of varied types of soil gave very nearly constant results, approximately 0.0032° C. depression for each 100 p. p. m. of total solids in the solution. The writers have obtained closely similar figures for the soils used in this investigation as is made evident by the following data:

Freezing-point depression per 100 p. p. m. of total solids

Soil No.	°C.
2	0.0032
4	.0031
9	.0032
10	.0030
8	.0034
5	.0030
Average	.0032

By the use of this constant the approximate strength of the soil solution in terms of parts per million of total solids may be calculated, and this has been done in Table VII.

TABLE VII.—*Comparison of total solids in soil solution as calculated by freezing-point and extraction methods*

Date.	Soil No.	Total moisture.	Free water.	Freezing-point depression.	Concentration of total dissolved solids calculated from freezing-point depression.	Concentration of total dissolved solids calculated from extracts to free water.	Total dissolved solids in 100 grams of moist soil calculated from freezing-point depression.	Total dissolved solids in 100 grams of moist soil calculated from extracts.
		Per ct.	*Per ct.*	°C.	*P. p. m.*	*P. p. m.*	*Gm.*	*Gm.*
Nov. 15	4A	17.3	4.3	0.068	2,100	10,000	0.009	0.043
Do	4B	16.7	3.7	.082	2,600	15,000	.010	.055
Do	5A	16.8	3.8	.079	2,500	7,500	.010	.029
Do	5B	17.5	4.5	.088	2,800	8,900	.013	.040
Do	6A	24.1	6.4	.068	2,100	4,900	.013	.031
Do	6B	24.4	6.7	.101	3,200	6,900	.021	.046
Do	7A	14.9	8.9	.082	2,600	3,400	.023	.030
Do	7B	13.6	7.6	.151	4,700	6,400	.036	.049
Do	12A	14.4	10.4	.061	1,900	1,500	.020	.016
Do	12B	11.4	7.4	.138	4,300	4,800	.032	.036
Do	14A	17.5	10.0	.033	1,000	2,800	.010	.028
Do	14B	16.2	8.7	.095	3,000	6,300	.026	.055
Dec. 21	1A	23.4	5.4	.037	1,200	4,800	.006	.026
Do	1B	22.3	4.3	.095	3,000	12,400	.013	.053
Do	2A	20.4	7.4	.047	1,500	2,800	.011	.021
Do	2B	20.0	7.0	.087	2,700	6,300	.019	.044
Do	3A	20.9	6.9	.048	1,500	4,200	.010	.029
Do	3B	20.7	6.7	.060	1,900	5,600	.013	.038
Do	8A	12.7	8.7	.049	1,500	3,200	.013	.028
Do	8B	12.5	8.5	.111	3,500	7,500	.030	.064
Do	9A	11.0	5.0	.031	1,000	3,700	.005	.019
Do	9B	10.6	4.6	.058	1,800	6,200	.008	.029
Do	10A	15.1	7.1	.046	1,400	2,800	.010	.020
Do	10B	14.6	6.6	.079	2,500	5,700	.017	.038
Do	11A	14.5	8.5	.047	1,500	3,600	.013	.031
Do	11B	13.6	7.6	.134	4,200	6,600	.032	.050
Dec. 27	4A	19.3	6.3	.055	1,700	8,300	.011	.052
Do	4B	18.0	5.0	.121	3,800	14,800	.019	.074
Do	5A	18.2	5.2	.066	2,100	7,700	.011	.040
Do	5B	18.0	5.0	.106	3,300	13,300	.017	.067
Do	6A	24.5	6.8	.085	2,700	6,100	.018	.042
Do	6B	24.8	7.1	.103	3,200	10,100	.023	.072
Do	7A	15.9	9.9	.038	1,200	2,700	.012	.027
Do	7B	14.7	8.7	.108	3,400	7,800	.030	.068
Do	12A	13.9	9.9	.030	900	2,400	.009	.024
Do	12B	12.7	7.7	.059	1,800	4,300	.014	.033
Do	14A	17.0	9.5	.039	1,200	3,400	.011	.032
Do	14B	16.5	9.0	.068	2,100	4,800	.019	.043
Feb. 12	1A	22.7	4.2	.056	1,700	10,800	.007	.045
Do	1B	21.7	3.2	.108	3,400	21,700	.011	.069
Do	2A	20.2	7.2	.056	1,700	6,700	.012	.049
Do	2B	20.2	7.2	.101	3,200	7,600	.023	.055
Do	3A	20.6	6.6	.062	1,900	5,300	.013	.035
Do	3B	19.9	6.9	.120	3,800	6,100	.026	.042
Do	8A	10.6	6.6	.062	1,900	4,800	.013	.032
Do	8B	10.8	6.8	.135	4,200	7,900	.029	.054
Do	9A	9.4	3.4	.057	1,800	8,600	.006	.029
Do	9B	9.5	3.5	.087	2,700	11,100	.009	.039
Do	10A	14.1	6.1	.066	2,100	4,900	.013	.030
Do	10B	13.4	5.4	.125	3,900	9,400	.021	.051
Do	11A	13.3	7.3	.065	2,000	4,900	.015	.036
Do	11B	13.5	7.5	.133	4,200	8,300	.032	.062

TABLE VII.—*Comparison of total solids in soil solution as calculated by freezing-point and extraction methods*—Continued

Date.	Soil No.	Total moisture.	Free water.	Freezing-point depression.	Concentrated total dissolved solids calculated from freezing-point depression.	Concentrated total dissolved solids calculated from extracts to free water.	Total dissolved solids in 100 grams of moist soil calculated from freezing-point depression.	Total dissolved solids in 100 grams of moist soil calculated from extracts.
		Per ct.	*Per ct.*	*°C.*	*P. p. m.*	*P. p. m.*	*Gm.*	*Gm.*
Feb. 19.....	4A	17.6	4.6	0.098	3,100	8,800	0.014	.041
Do.....	4B	17.2	4.2	.148	4,600	16,000	.019	.067
Do.....	5A	18.1	5.1	.106	3,300	7,100	.017	.036
Do.....	5B	17.2	4.2	.115	3,600	11,900	.015	.050
Do.....	6A	24.8	7.1	.066	2,100	4,900	.015	.035
Do.....	6B	25.0	7.3	.126	3,900	7,500	.029	.055
Do.....	7A	14.6	8.6	.053	1,700	2,900	.015	.025
Do.....	7B	14.0	8.0	.093	2,900	5,300	.023	.042
Do.....	12A	12.7	8.7	.043	1,300	2,300	.011	.020
Do.....	12B	11.4	7.4	.083	2,600	3,900	.019	.029
Do.....	14A	16.1	8.6	.063	2,000	3,900	.017	.034
Do.....	14B	15.0	7.5	.123	3,900	7,200	.029	.054

Upon several occasions the total solids were determined in the 1-to-5 extracts of all soils. These were also calculated in terms of concentration of total soil moisture, as well as of free soil water. From the depressions of the freezing point, calculations were made of concentrations expressed as total solids in parts per million of the soil solution with the constant just described (Table VII). The first and most striking observation based on these results is that the relation between the total solids in the extracts of cropped and uncropped soils is also manifested by the depressions of the freezing point. In fact, throughout the experiment this correlation was noted. The fluctuations of the important nutrient elements in the water extracts already described by Stewart were in general agreement with the changes in the concentration of the soil solution. The low and high points came at about the same periods of the growing season in both cases.

From these considerations it might seem justifiable to assume that the material present in the actual soil solution forms at least an important fraction of the total solids dissolved in the 1-to-5 extract. It is, however, highly improbable that an extract should consist exclusively of the material present in the soil solution. Necessarily an additional quota would be derived from other more or less soluble substances, and the quantity dissolved would depend upon the conditions of extraction. A number of years ago Mitscherlich (*6*), in an important study on extracts of soils prepared with carbonated water, emphasized this point of view. His procedure consisted in making extracts with varying proportions of carbonated water, ranging from 5 to 1 up to 30 to 1. From the data so

obtained he constructed graphs and proved that with increasing quantities of water more material was dissolved. He therefore divided the total dissolved solids into two fractions: (a) That part soluble even with low moisture content, and (b) the additional material dissolved by the excess of solvent.

A number of difficulties arise in connection with this method of arriving at the concentration of soil solution. In the first place, it is not safe to assume that a curve based on one range of extractions can accurately be extended to cover another range of extractions. Indeed, the experimental data indicate that with the smaller proportions of water the curves may change their direction very appreciably and it is unfortunately impracticable to obtain extracts for analysis in those concentrations which correspond to optimum moisture conditions. Another limiting factor, previously neglected, has been described by Stewart. This concerns the differential effect of the solvent. The actual solvent in any case is not pure water, but pure water plus the solids already dissolved in the soil solution, and these vary enormously with changing conditions, even in the same soil. It is quite obvious that this factor would modify any calculations of the concentration of the soil solution based on water extracts. Moreover, a question may arise with regard to the relation of the soil extract to the residual solution. It is possible that the equilibrium may not be the same for the low and high proportions of water, especially in soils of colloidal character.

Notwithstanding these difficulties met with in attempting to predict accurately the concentration of the soil solution from soil extracts, it is still possible to make certain valuable comparisons of the two methods. If we should contrast the concentration of the soil solution, calculated from the extracts to the total moisture of the soil, with the concentrations shown by the freezing-point method, there would be a general similarity of magnitude. Logically, however, a comparison is much more justifiable when the extracts are calculated not to the total soil water, but to the free water, in the sense meant by Bouyoucos. It is then apparent that the concentration of the soil solution calculated by the extraction method is from two to five times that indicated by the depressions of the freezing point (Table VII). In other words, there is a considerably greater quantity of total solids dissolved in the 1-to-5 extract than is actually present in the soil solution at any given moment. The general order of magnitude of the two quantities is, however, evidently not disproportionate, the material extracted from the sandy loams averaging only about twice the quantity actually present in the soil solution, as shown by the freezing-point method.

The total amounts of dissolved material in 100 gm. of soil have been calculated by multiplying the percentages of free water by the concentrations in terms of parts per million of total solids. If we use the

freezing-point depressions as a basis, it appears that from 0.01 to 0.03 gm. of total solids is in solution for each 100 gm. of moist soil, while the total solids obtained by 1-to-5 extractions vary from 0.02 to 0.06 gm. per 100 gm. of soil.

In order to obtain approximate estimates of the material dissolved in an extract additional to that present in the soil solution, two soils (No. 5 and 8) were subjected to the procedure of successive extraction. One kgm. of each soil was extracted with a total of 10 liters of distilled water. Ten extractions were made, with 1 liter of water for each extraction. The results of the 10 extracts are plotted in figure 9. It will be noted that the first extract contained a very much greater quantity of dissolved solids than any subsequent extract. It was suggested by Stewart that some idea of the extra dissolved material might be formed by using as a basis of calculation the quantity dissolved in each liter after the extracts had become relatively constant. Thus, for soil 5 roughly 150 p. p. m. of total solids were found in each of the later extracts, and for soil 8, 100 p. p. m. By assuming that the rate of solubility is uniform, in a 1-to-5 extract there would be 5 times 150, or 750, p. p. m. of extra material dissolved in the case of soil 5, and 500 p. p. m. for soil 8. The total solids dissolved from 1 kgm. of soil by 5 liters of water aggregate 1,300 and 1,100 p. p. m. of total solids, respectively. This means that not more than 50 per cent could have originally been present in the soil solution. If this correction were applied to the extracts, the agreement with the data obtained by the freezing-point method would in some cases be fairly close, but usually the extracts would still give somewhat higher results. This fact is reasonably explained on the assumption that the first liter of solvent has dissolved out some material relatively soluble although not actually present in the soil solution, while the later extracts contain only difficultly soluble substances.

GENERAL DISCUSSION

It will now be well to correlate certain broad relations which may be deduced from the data presented in this paper through some further reference to the principal investigation of this series by Stewart. It should be emphasized again that neither from the water extraction nor freezing-point methods is there any evidence that the soil solution has a constant composition. On the contrary, the soil solution even of the same soil may vary greatly under different conditions. The water-extraction method indicates that this variation may occur with all the principal nutrient elements with the exception of phosphorus. These data accord with the view expressed by Bouyoucos and McCool, that the soil solution should not be considered as saturated. The opposite conception as outlined in the earlier work of Whitney and Cameron (*9*) is not upheld by the present investigation. If the great excess of nearly insoluble minerals in a soil were the determining factor in the soil solu-

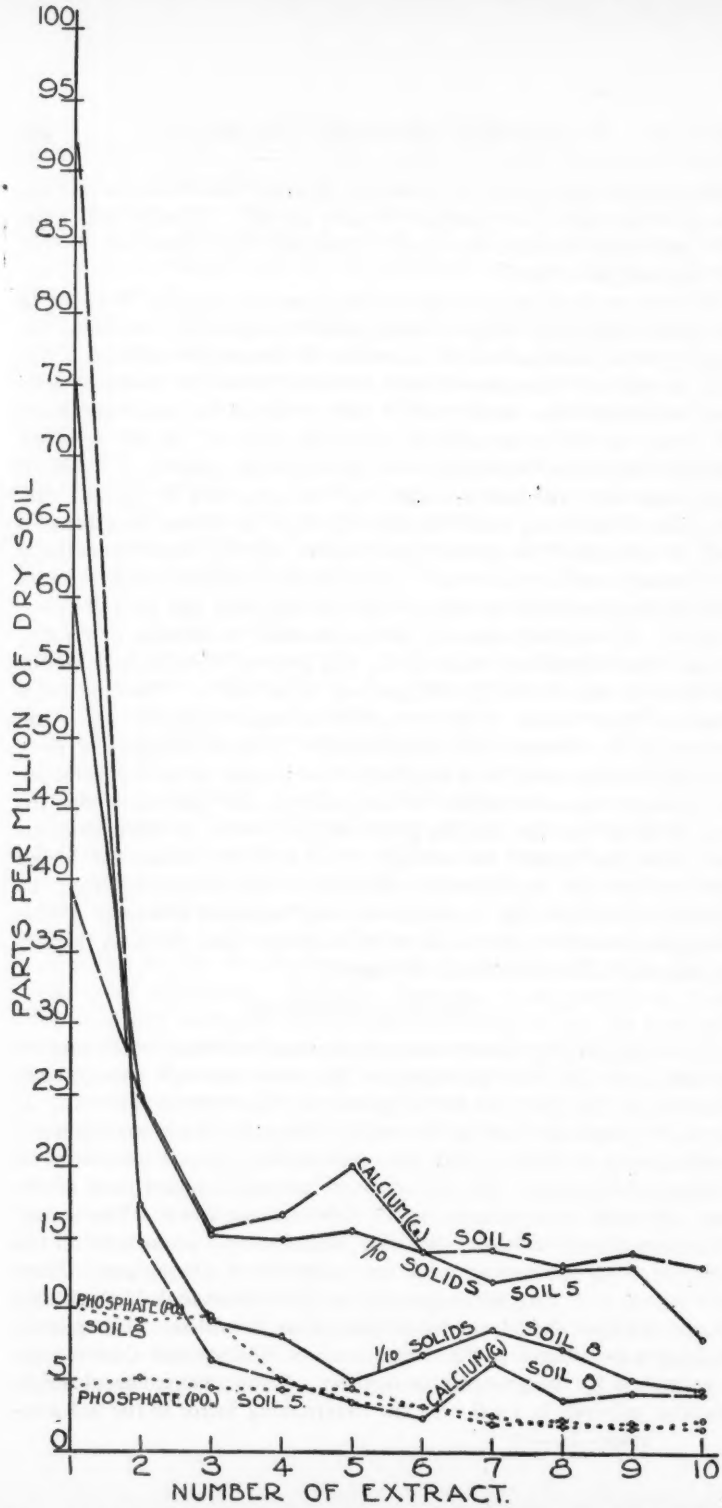

FIG. 9.—Graphs showing the results of successive extractions of soils 5 and 8. One liter of water to 1 kgm. of soil for each extraction was used.

tion, then its concentration in the cropped soil should not be strikingly diminished over a long period of time after the crop is removed, which in fact is the case. Also the soil solution in a leached soil has a greatly diminished concentration which is not markedly increased by long standing. In brief, the evidence is quite opposed to the theory that there is an immediate restoration of equilibrium when the soil solution is diminished in concentration by the plant or other agency.

One explanation of the fluctuations in the soil solution lies most probably in the varying nature of the solvent, especially in its content of carbon dioxid, which may well be one of the preponderating factors. The effect of carbon dioxid on the solution of soil minerals has been demonstrated by Mitscherlich, and the present investigation has indicated the effect of carbon dioxid in increasing the depression of the freezing point. It is generally conceded that the partial pressure of carbon dioxid in the soil atmosphere is greater than that of the outside air. Russell (7) has shown that the content of carbon dioxid in the soil may vary greatly at different times of the year, according to the intensity of bacterial action. In addition to carbon dioxid, other products of bacterial activity may have a further influence, the extent of which is still problematical.

It has been a general teaching of agricultural art that soil fertility is increased by those operations which tend to bring about optimum biological conditions in the soil. The experiments recorded in this investigation seem to afford direct evidence that the soil solution may be greatly affected by the activity of microorganisms and indirectly therefore by cultivation, temperature, organic matter, etc. Finally, the results of the experiments reported in this paper have considerable significance to the plant physiologist, since comparisons may be made between osmotic pressures in nutrient solutions and in the soil solution as it actually exists in the soil under conditions favorable to crop growth. It will be observed that in none of the soils did the plants obtain their nutriment from a highly concentrated solution. The general range of concentrations was from a maximum of 0.5 or 1.0 atmosphere to a minimum of 0.1 or 0.2 atmosphere. Under the conditions of approximately optimum moisture contents there was no sharp distinction between the silty clay loams and the fine sandy loams. By lowering the moisture content of the clay loams considerably, it is true that a very high concentration of the soil solution results, but under moisture conditions favorable to plant growth the solution is dilute. From certain of the soils stored in the bins a different idea of the concentration of the soil solution might be obtained, since this treatment has in some cases greatly increased the soluble material. The true conception of the nature of the nutrient media in soils can only be attained when soils are studied throughout the season under conditions suitable for crop growth.

Preliminary experiments have been carried out with the use of sand and water-culture methods with the nutrient solutions whose concentrations are comparable with those of the soil solution. The results have indicated that the osmotic pressures existing in the soil are also most favorable to the growth of barley in culture solutions. When considerably greater concentrations are maintained, decreased yields result, while very much lower osmotic pressures are suboptimum. Further experiments are now in progress.

It has not been possible in this investigation to make any general correlation with crop yield, although it is worthy of note that the two soils of lowest production, No. 9 and 12, show consistently low concentrations of the soil solution and also yield water extracts containing exceptionally small quantities of nutrient elements. In the discussions of Stewart and Burd the relations of chemical analysis of the medium to crop production are discussed more completely.

SUMMARY

(1) Freezing-point depressions have been determined on 13 soils under a variety of conditions.

(2) The concentration of the soil solution has been found to vary with the season and also as a result of treatment with carbon dioxid, leaching, incubation, etc.

(3) The growth of a crop markedly diminishes the concentration of the soil solution. This effect is still evident at the beginning of the following season.

(4) The soil solutions under conditions favorable to crop growth were found to be very dilute, particularly at the height of the growing season.

(5) Certain general agreements between the extraction and freezing-point methods are discussed.

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